Neutrinos: A History

Neutrino Mixing

Current Accelerator Expts

NuMI/MINOS

T2K

Next Generation Reactor Expts

CP Violation

LBNE

Summary

The Neutrino Physicist's Billion Dollar Toolkit

BNL Physics Dept. Colloquium, 04/06/2010

Mary Bishai
Brookhaven National Laboratory

April 6, 2010

Outline

1 Neutrinos: A History

2 Neutrino Mixing

3 Current Accelerator Expts
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A BRIEF HISTORY OF THE NEUTRINO

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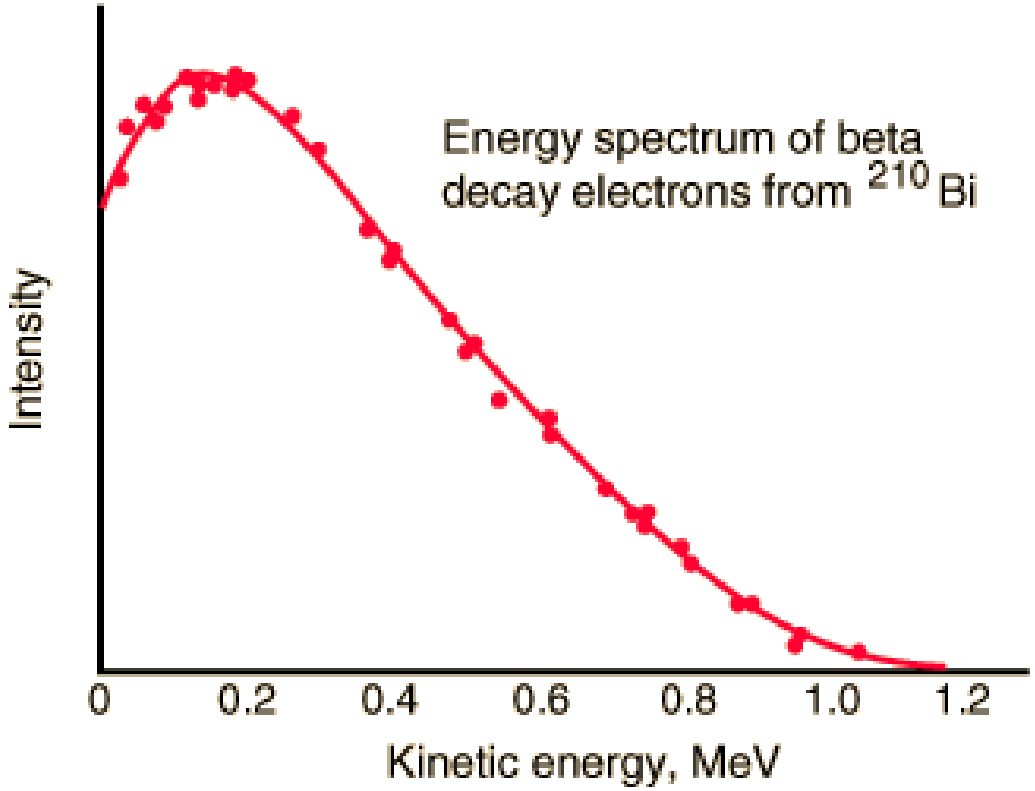
Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



G.J Neary, Proc Phys. Soc., A175, 71 (1940)

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Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen proposes that a neutrally charged "neutron" with a mass "$<$ 0.01 proton mass" is emitted in beta-decays.

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

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1932: James Chadwick discovers the neutron - its too heavy - cant be Pauli's particle

James Chadwick

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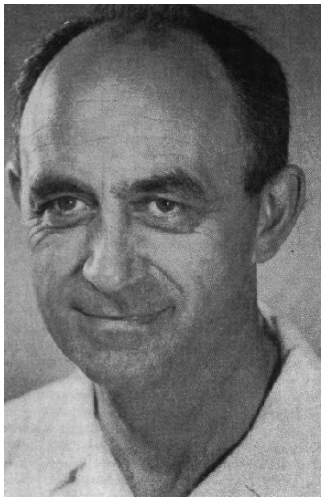
Solvay Conference, Bruxelles 1933: Fermi proposes to name Pauli's particle the "neutrino".



Enrico Fermi

The Theory of Weak Interactions

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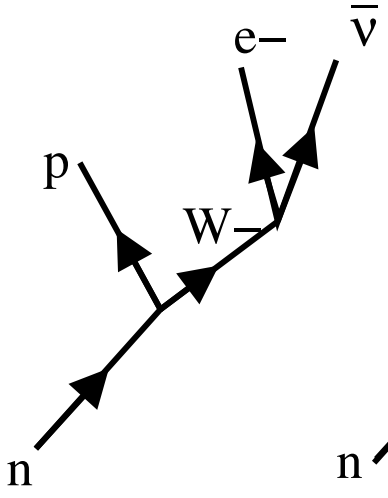
$\geq$ **1933:** **Fermi builds his theory of weak interactions and beta decay**

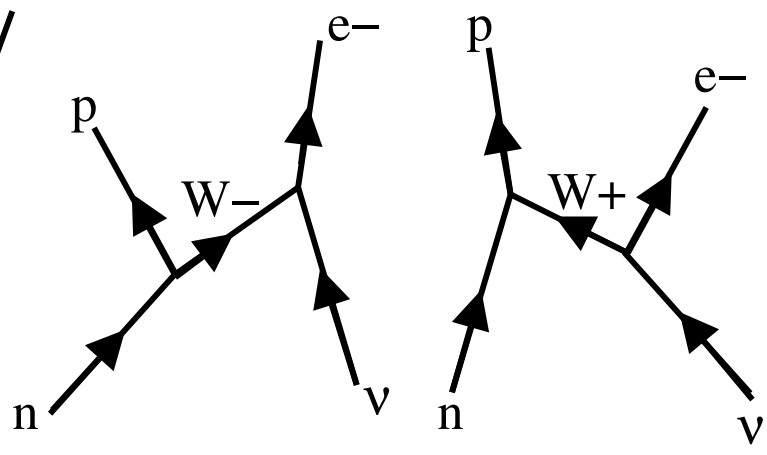
Charged current interactions

Decay of neutron



$n \rightarrow p + e^- + \bar{\nu}$

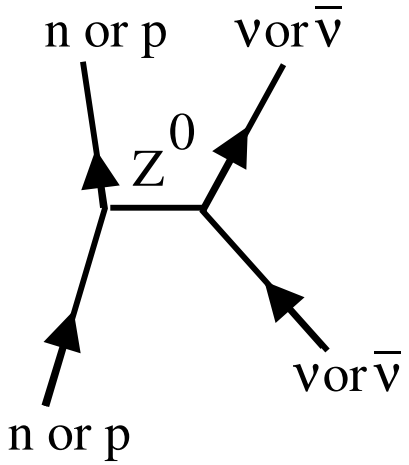
Neutrino interacts with neutron



$n + \nu \rightarrow p + e^-$

Neutral current interactions

n or p interacts with neutrino or antineutrino



The Lepton Family and Flavors

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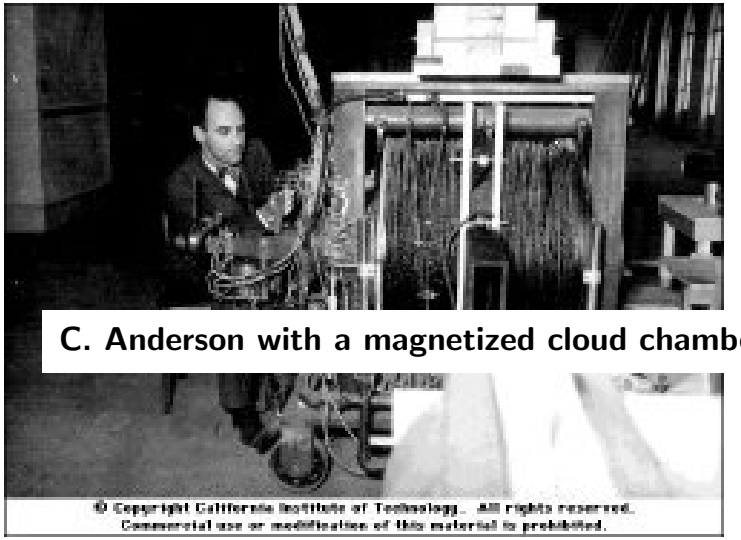
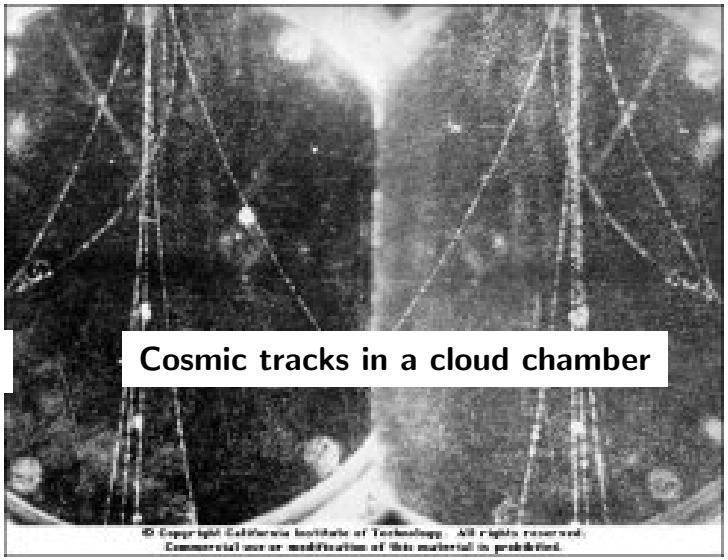
1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).



C. Anderson with a magnetized cloud chamber



Cosmic tracks in a cloud chamber

Weak decays of muons: $\mu^{+/-} \rightarrow e^{+/-} + \nu\bar{\nu}$

mass$_\mu$ = 207 mass$_e$ = 105.7 MeV/c^2, $\tau = 2.2\mu$ sec .

I. I Rabbi (founder of BNL): Who ordered THAT?

The muon and the electron are *different "flavors" of weakly interacting elementary particles called leptons*. **Neutrinos are neutral leptons. Do ν's have flavor too?**

Discovery of the Pion: 1947

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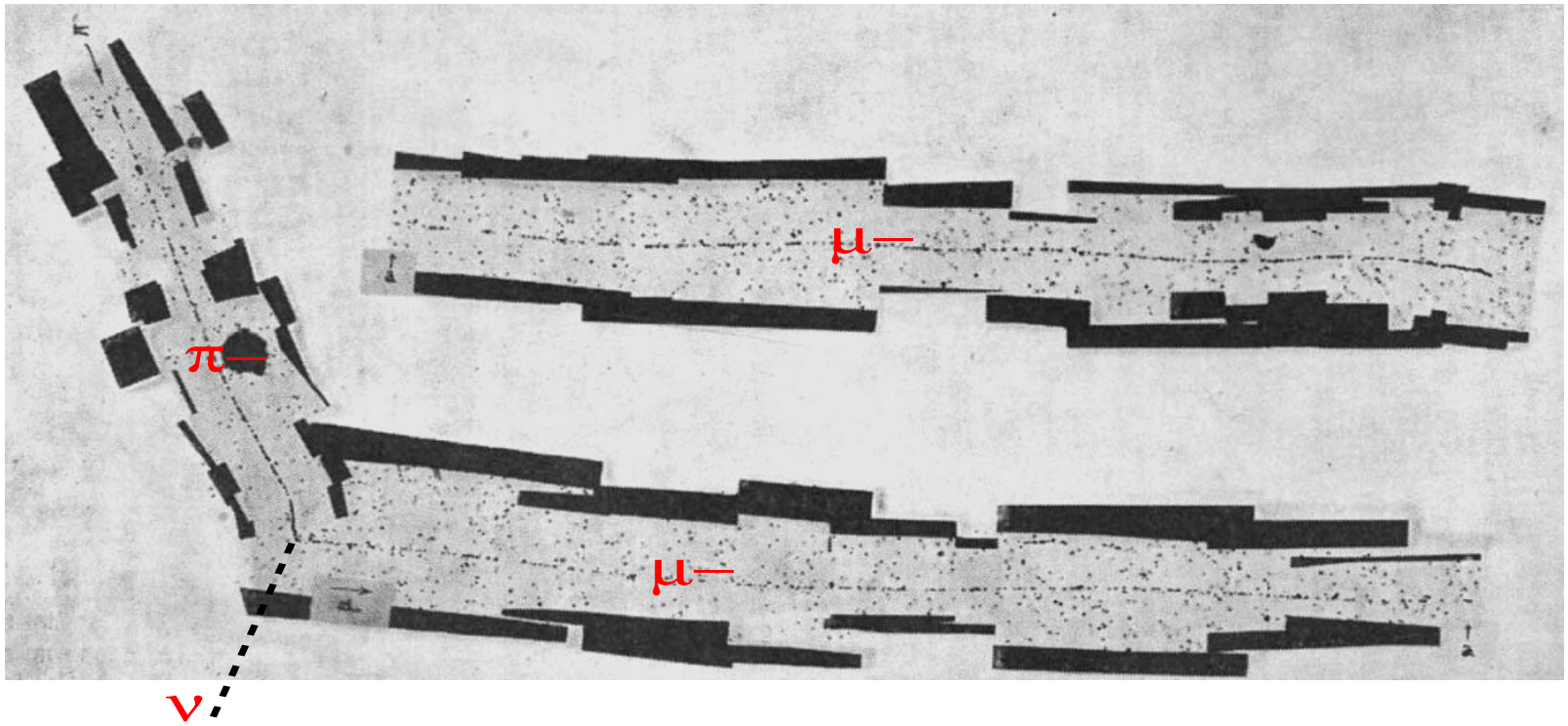
Cecil Powell takes emulsion photos aboard high altitude RAF flights. A charged particle is found decaying to a muon:



Weak decays of pi mesons (pions): $\pi^{+/-} \rightarrow \mu^{+/-} + \nu_X$

mass$_{\pi^-}$ = 0.15 mass$_{\text{proton}}$ = 139.6 MeV/c^2, τ = 26 ns.

Pions are composite particles from the "hadron" family which includes protons and neutrons.

Evidence for neutrinos in cosmic rays: invisible tracks

Finding Neutrinos...

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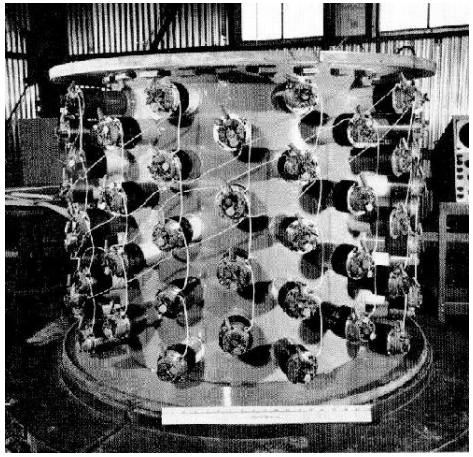
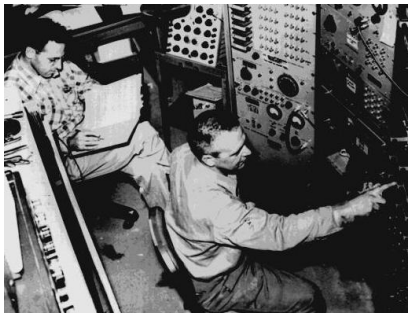
1950's: Fred Reines at Los Alamos and Clyde Cowan mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV + T_e^+)
3. $n + {}^{108}Cd \rightarrow {}^{109}Cd* \rightarrow {}^{109}Cd + \gamma$ ($\tau = 5\mu s$).



Neutrinos first detected using a nuclear reactor!

Neutrinos have Flavors

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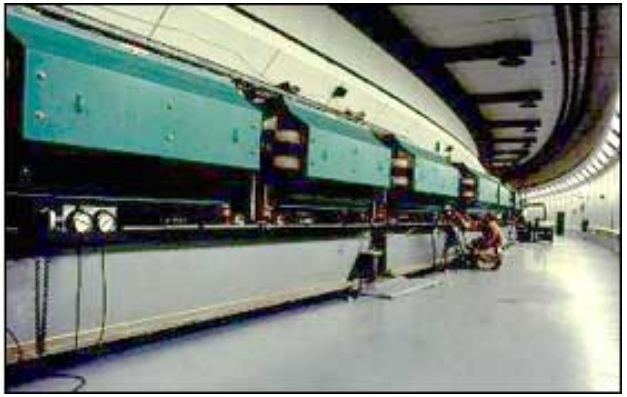
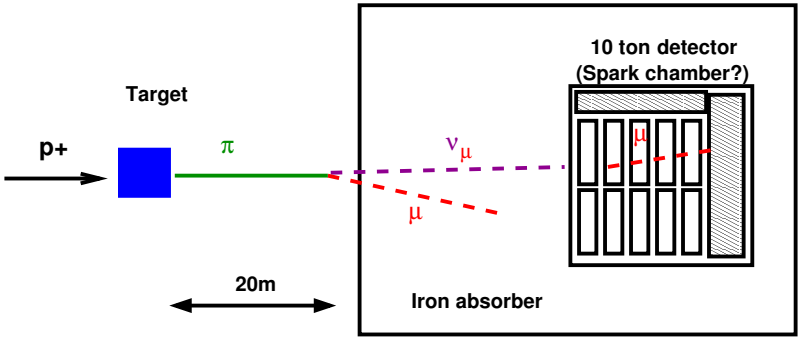
1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \longrightarrow \mu\nu_x$



The AGS



Making ν's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

The first accelerator neutrino experiment was at the AGS.

Number of Neutrino Flavors: Particle Colliders

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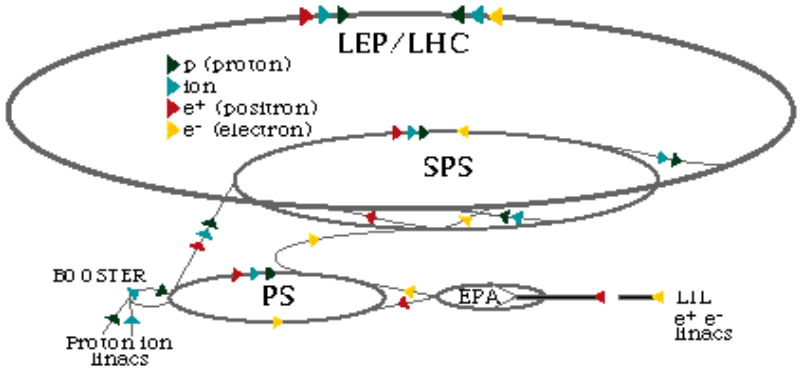
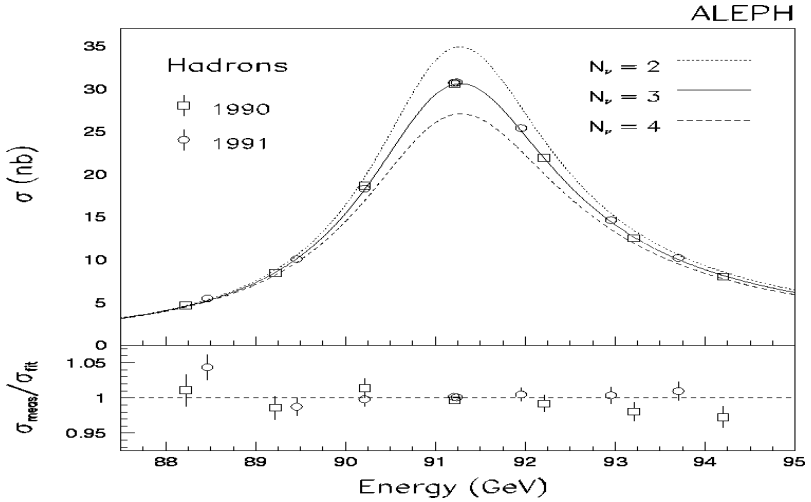
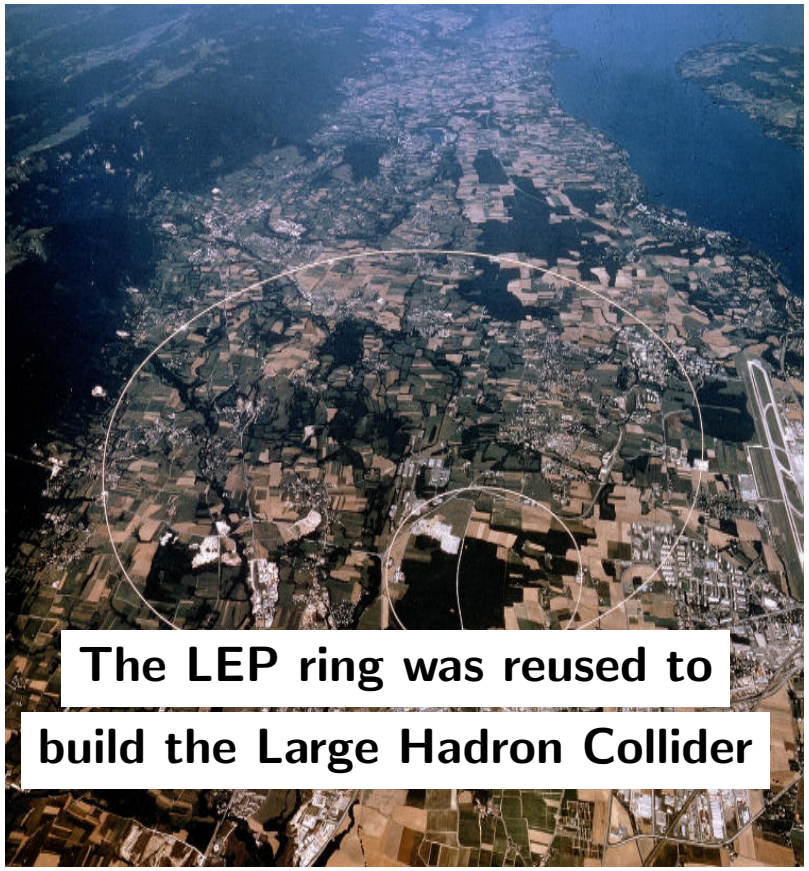
1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- particle colliders. $N_\nu = 2.984 \pm 0.008$

The LEP e^+e^- collider at CERN, Switzerland







The Particle Zoo

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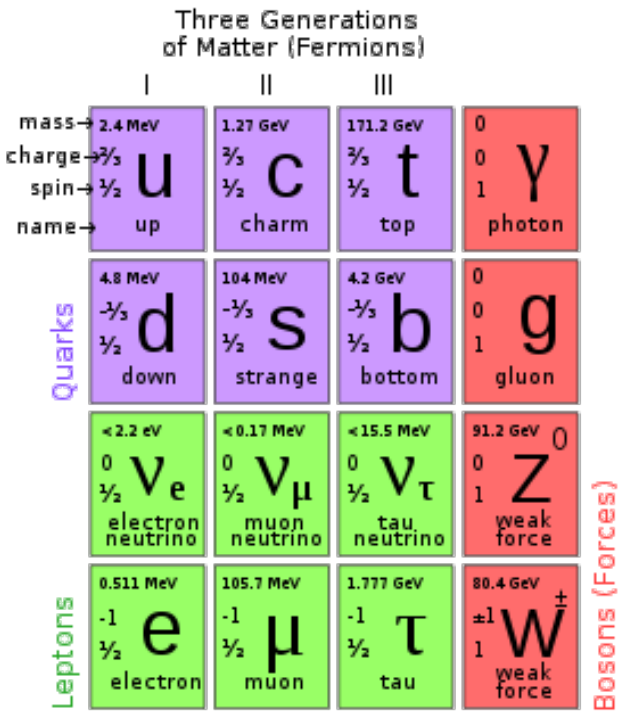

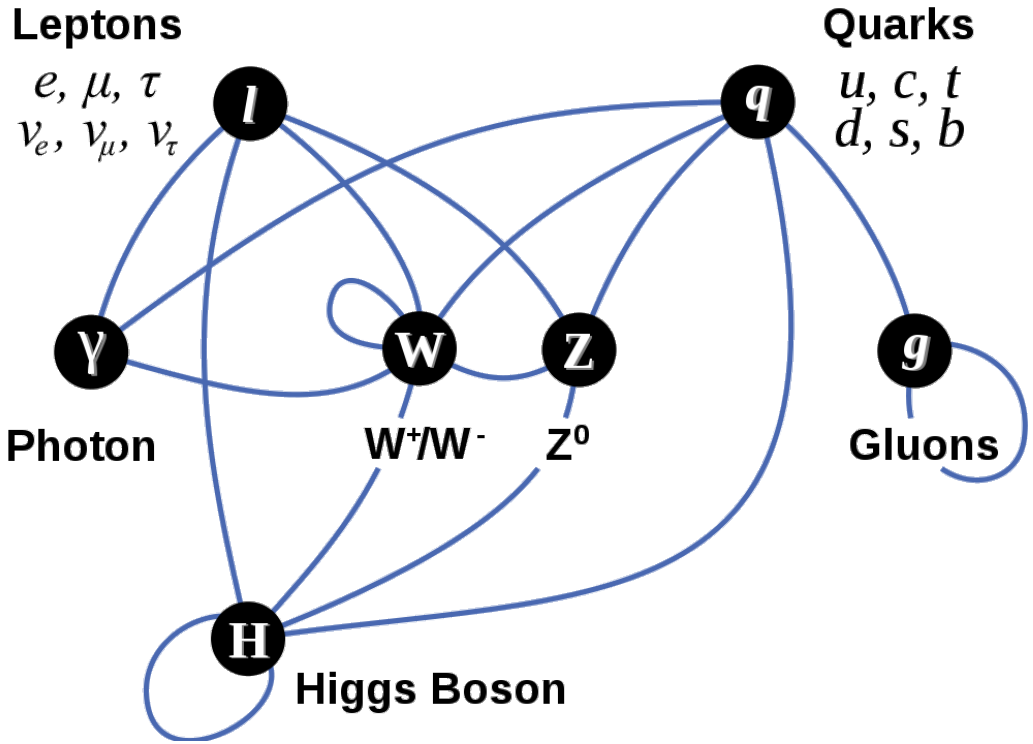

Sources of Neutrinos

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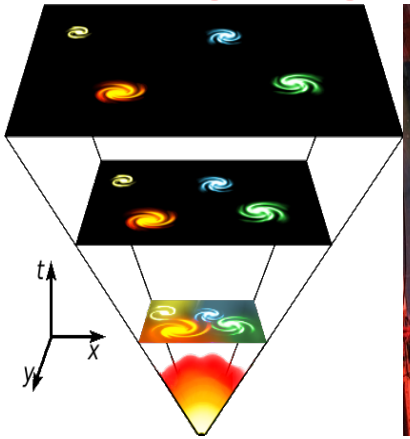
Big Bang

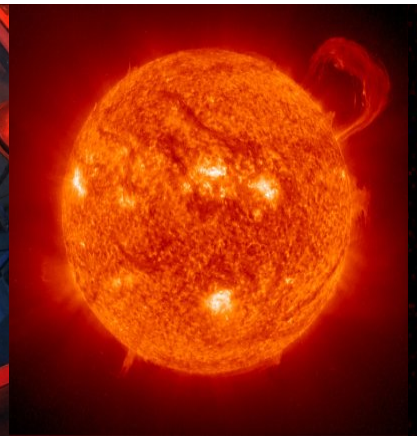


10^{-4} eV
$56/\mathrm{cm}^3$

Reactors

few MeV
$10^{21}/\mathrm{GW_{th}}/\mathrm{s}$

Sun

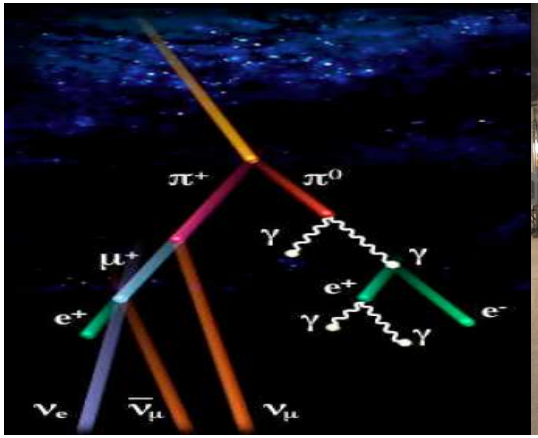


0.1-14 MeV
$10^{10}/\mathrm{cm}^2/\mathrm{s}$

SuperNova

$\sim$ 10 MeV
$10^{9}/\mathrm{cm}^2/\mathrm{s}$

Atmosphere

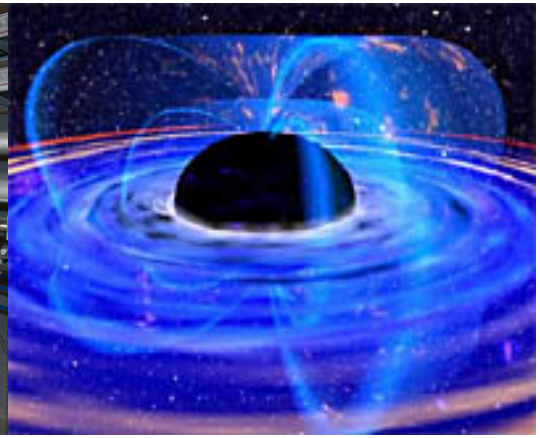


$\sim$ 1 GeV
$\mathrm{few}/\mathrm{cm}^2/\mathrm{s}$

Accelerators

1-20 GeV
$10^5/\mathrm{cm}^2/\mathrm{s}$ (at 1km)

Extragalactic



TeV-PeV
varies

Neutrinos and Todays Universe

Neutrino mass < 2 eV (beta-decay limits)

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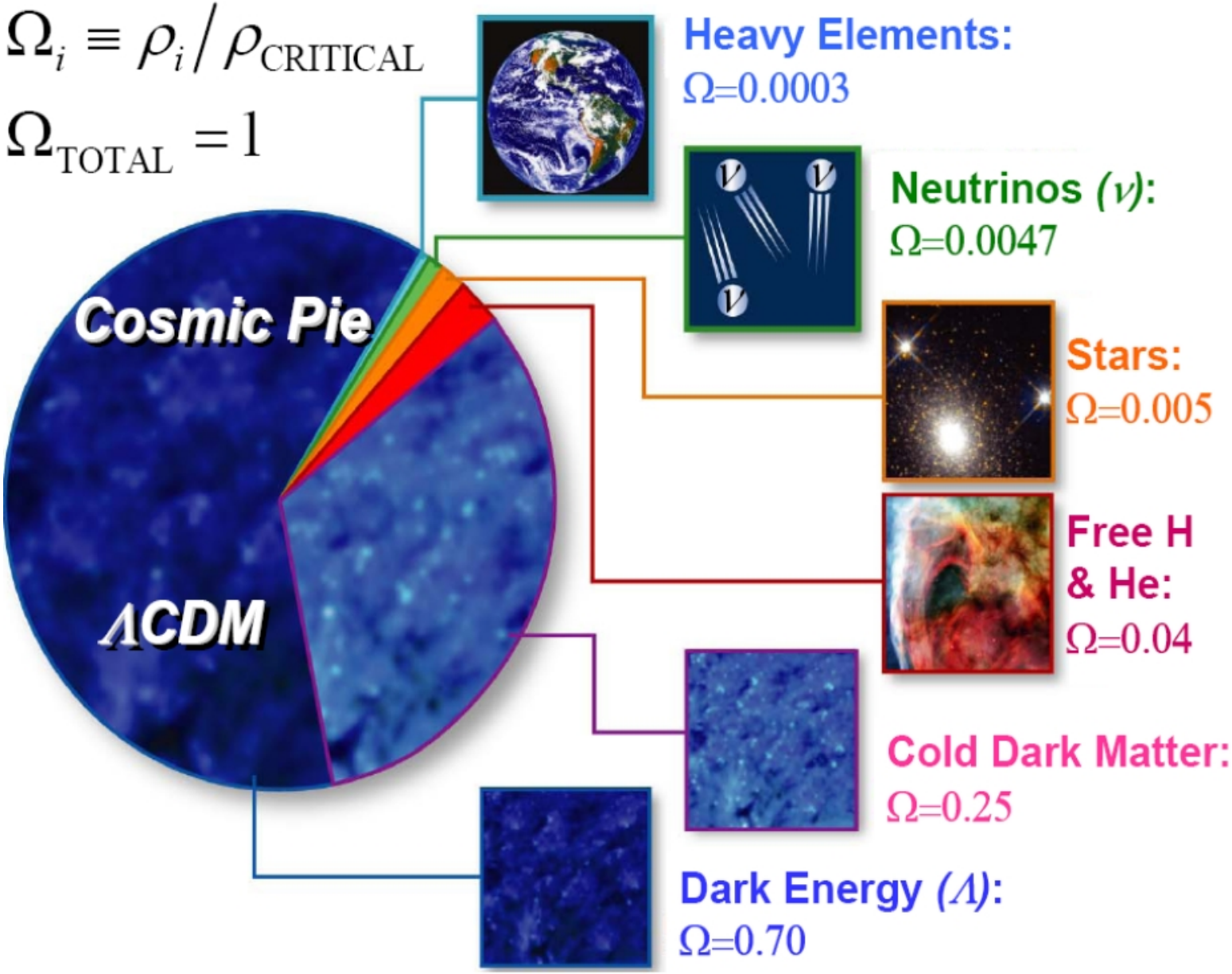
$$\Omega_i \equiv \rho_i / \rho_{\mathrm{CRITICAL}}$$

$$\Omega_{\mathrm{TOTAL}} = 1$$



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NEUTRINO MIXING AND OSCILLATIONS

Neutrino oscillations

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1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

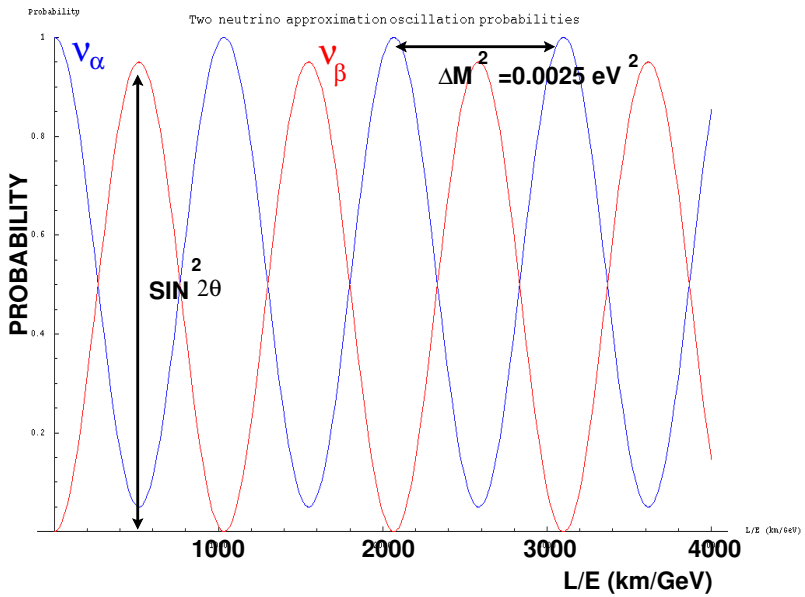
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m_2^2 - m_1^2)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



The Homestake Experiment

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1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

Ray Davis

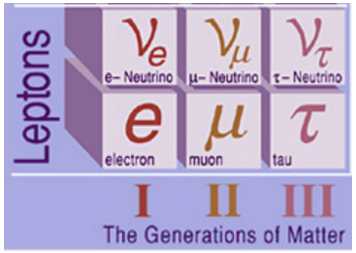
1. $\nu_e^{sun} + ^{37}\text{CL} \rightarrow e^- + ^{37}\text{Ar}$, $\tau(^{37}\text{Ar}) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.

Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

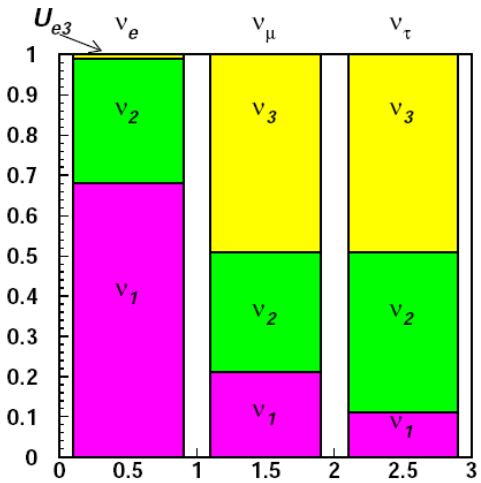
Solar ν_e disappearance $\Rightarrow$ first experimental hint of oscillations

Neutrino Mixing: 3 flavours

We know now of 3 flavours of neutrinos: The 3 flavour PMNS mixing matrix was developed in 1962 by Maki-Nakagawa-Sakata based on Pontecorvo's earlier work:



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



In the past 10 yrs we have measured most of the U_{PMNS} parameters

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & < 0.20\ ?? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

In contrast to CKM, large off diagonal terms:

The Super-Kamiokande Experiment

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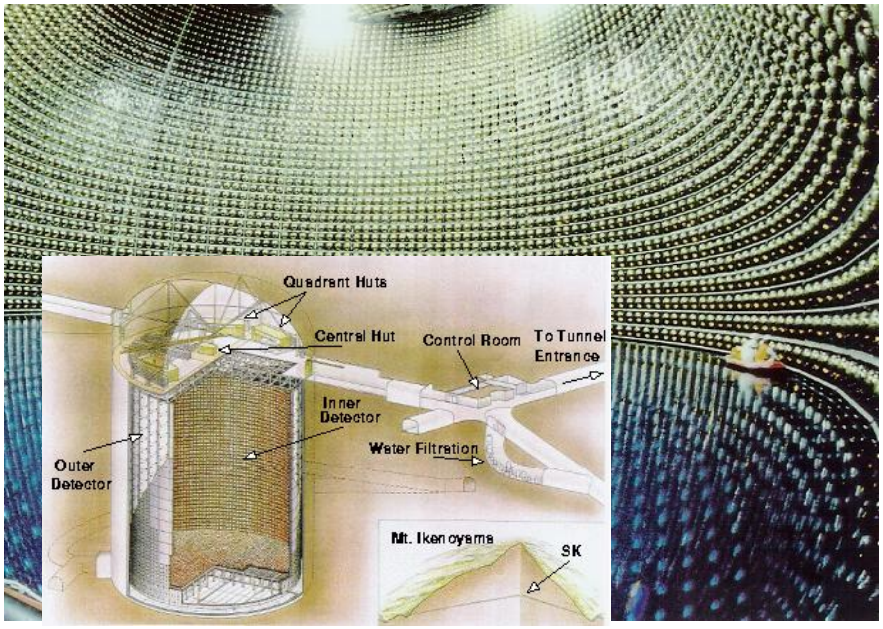
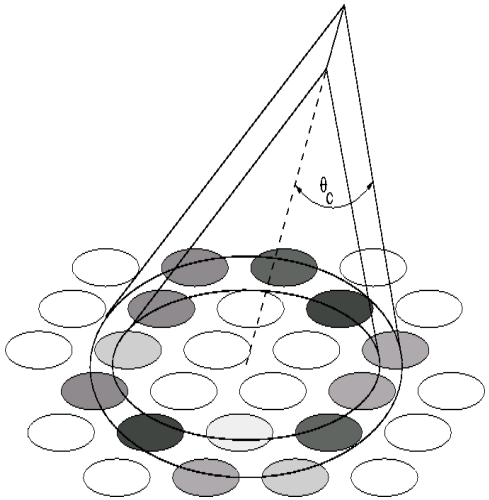
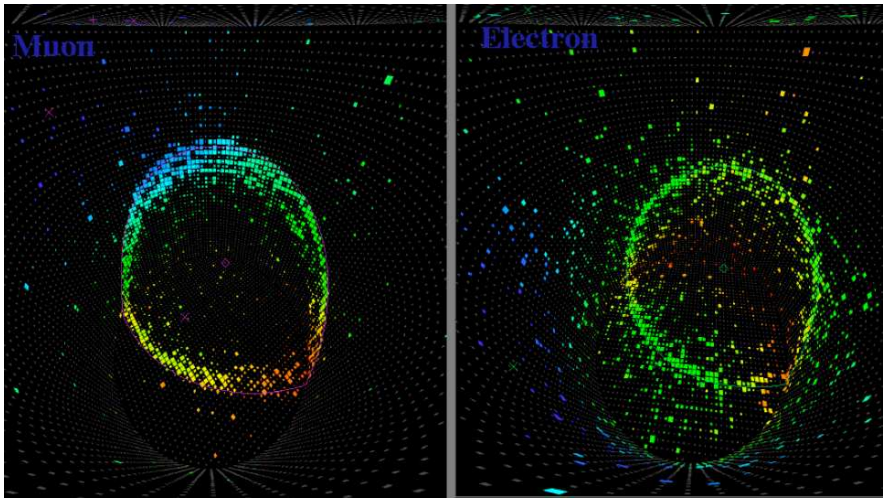
A huge 50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes. Located in an old zinc mine 0.6km under Mount Ikena in the Japanese Alps, near the town of Kamioka. The project has been collecting data since 1 April 1996.





Particle id using rings of Čerenkov light



Super-Kamiokande: Atmospheric ν_μ Disappearance

$2 \leftrightarrow 3$ mixing

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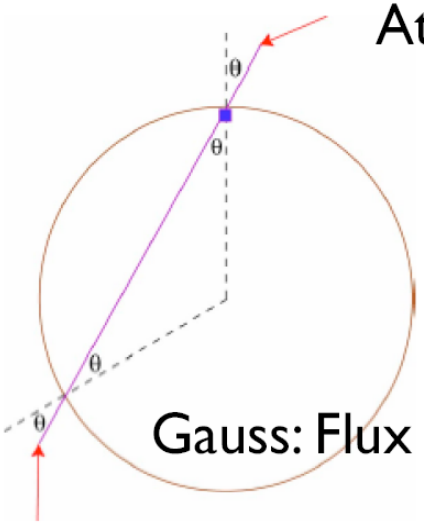
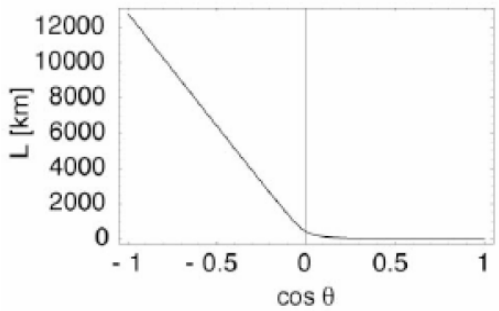
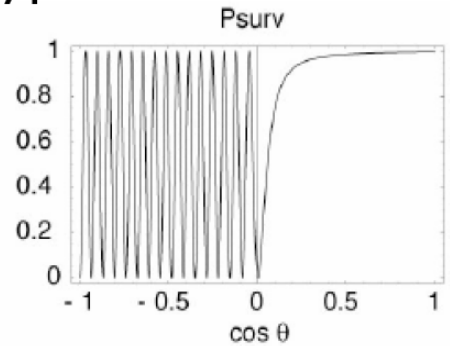
Atmospheric neutrinos as a source for oscillation experiments

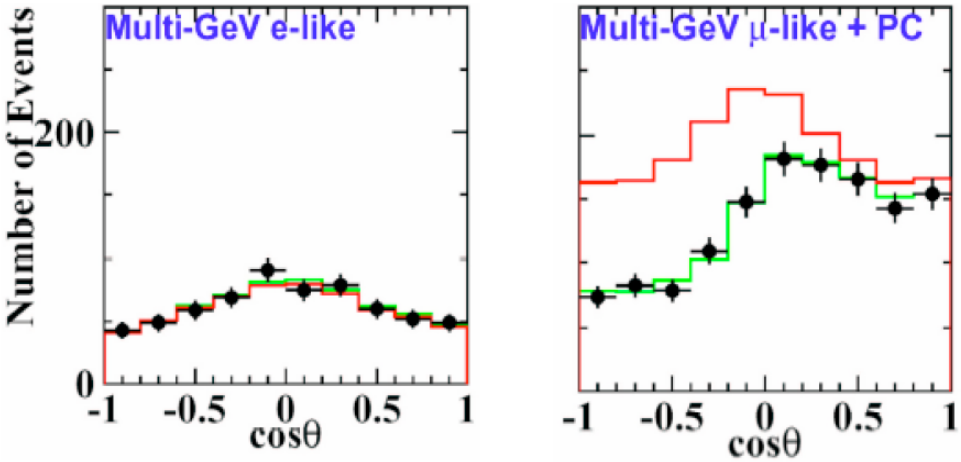
Atm. neutrinos 2:1 mu:e type







Gauss: Flux inside spherical shell isotropic



Evidence for neutrino oscillations from SuperK

Best fit : $(\sin^2 2\theta_{23}, \Delta m^2_{32}) = (1.02, 2.4 \times 10^{-3} \mathrm{eV}^2) \Rightarrow$ maximal mixing of 2,3 states!

SNO Experiment: Solar ν Measurments

$1 \leftrightarrow 2$ mixing

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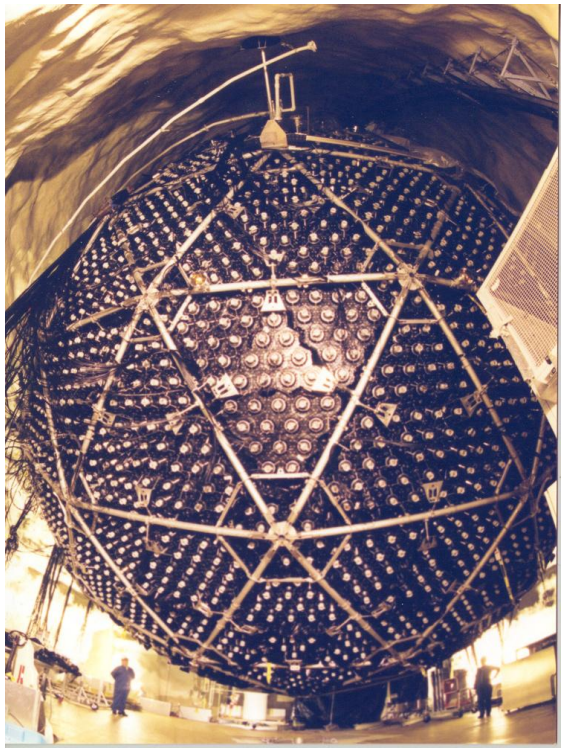

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:

$$1)\ \nu_e + d \rightarrow e^- + p + p \text{ (CC)}.$$
$$2)\ \nu_x + d \rightarrow p + n + \nu_x \text{ (NC)}.$$
$$3)\ \nu_x + e^- \rightarrow e^- + \nu_x \text{ (ES)}.$$

SNO measured:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

All the solar ν's are there but ν_e appears as ν_x!

KamLAND: Reactor $\bar{\nu}_e$ Measurements

$1 \leftrightarrow 2$ mixing

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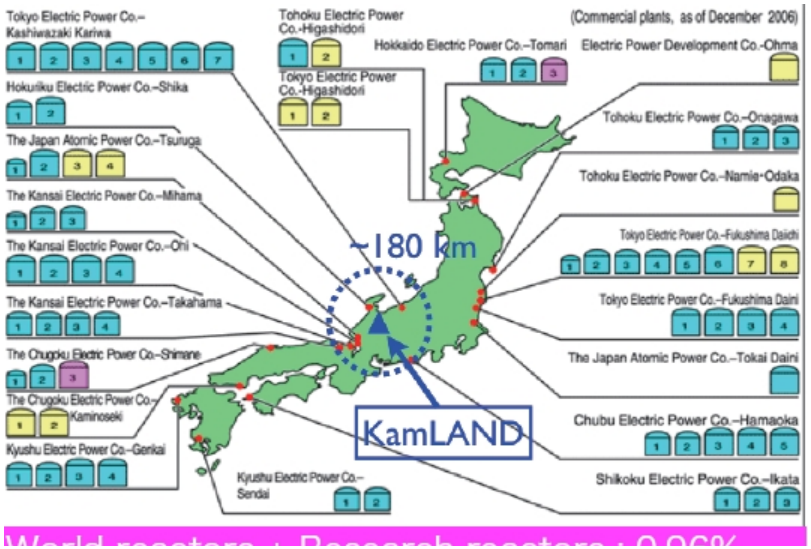
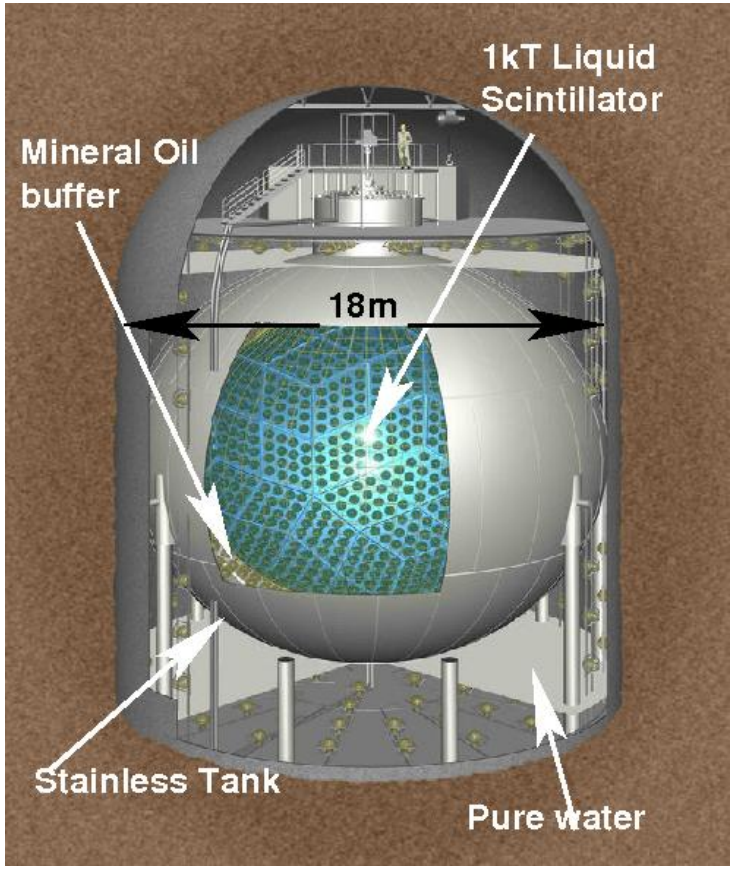
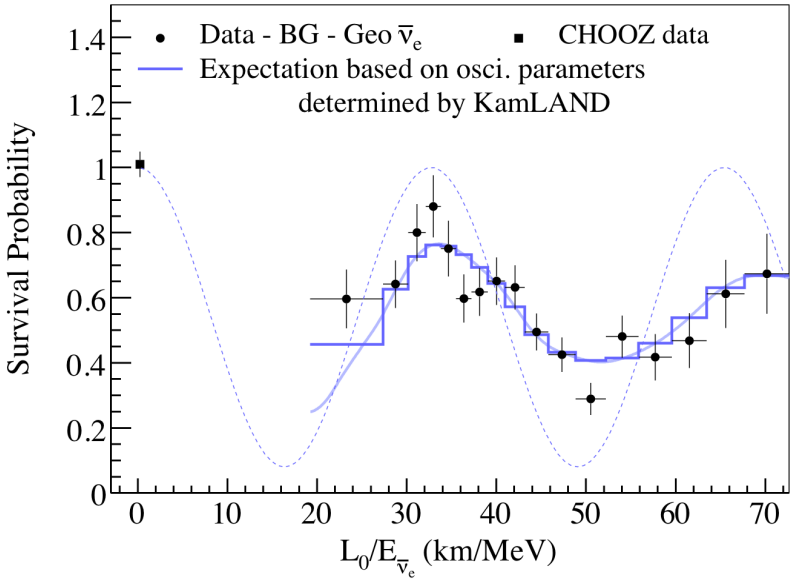






⇐ Clear wiggles!

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \text{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

The Implications of 3-Neutrino Mixing

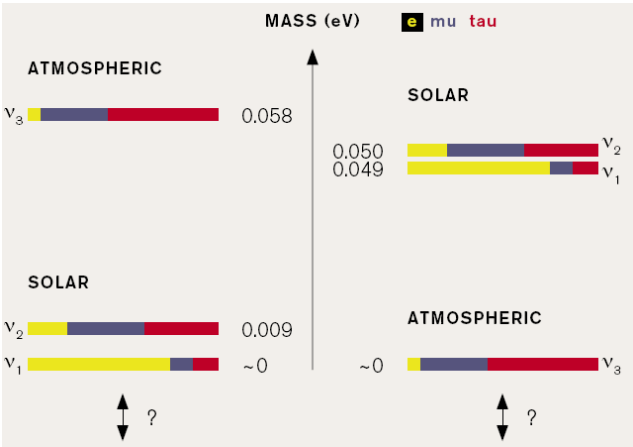
$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \to \nu_e,\ \text{reactor } \bar{\nu}_e \text{ disappear}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu_e,\ \bar{\nu}_e \text{ disappear}}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$



Normal Inverted

There are 3 quantum states mixing $\Rightarrow$ there is an overall phase: δ_{CP}.

If $\delta_{CP} \neq 0$ or π, charge-parity (CP) is violated and there is a $\nu/\bar{\nu}$ asymmetry.

Could this explain the origin of matter?

Is $\sin^2 2\theta_{13} = 0$? (no CP violation)

What is the value of δ_{CP}, sign(Δm^2_{31})?

Measuring ν_μ oscillations - Accelerator Expts

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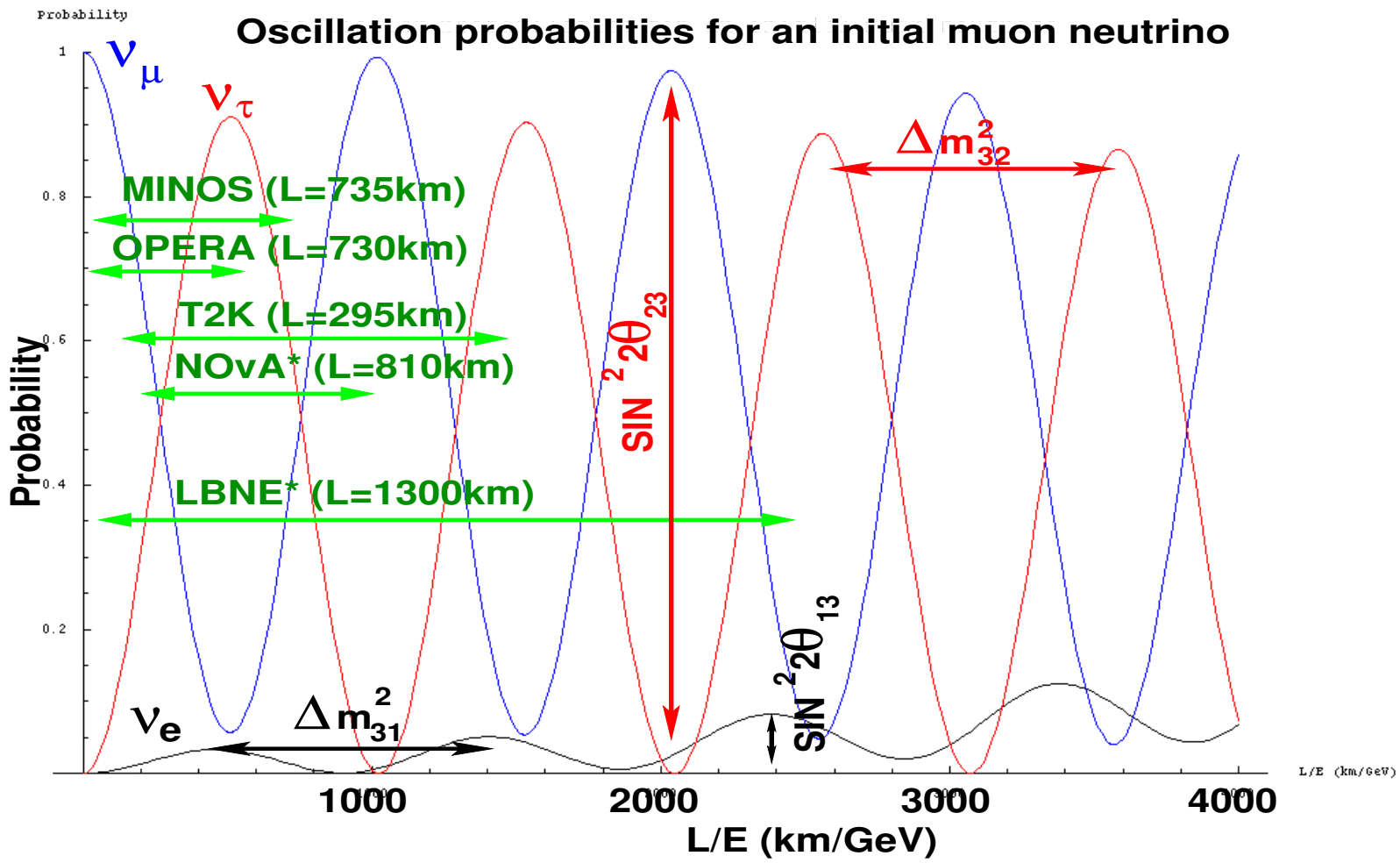

Accelerator expts access all 3-state oscillations using known $\nu/\bar{\nu}$ fluxes.

Can provide precision measurements of $\Delta m^2_{31,32}$, $\sin^2 2\theta_{13}$, δ_{cp}

Matter Effect on Neutrino Oscillation

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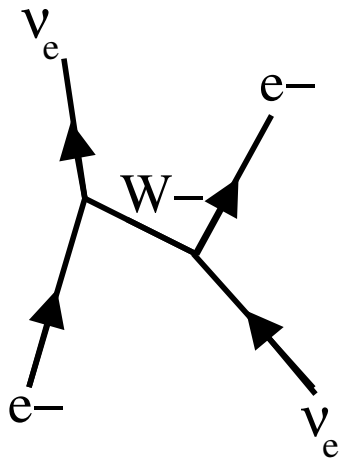
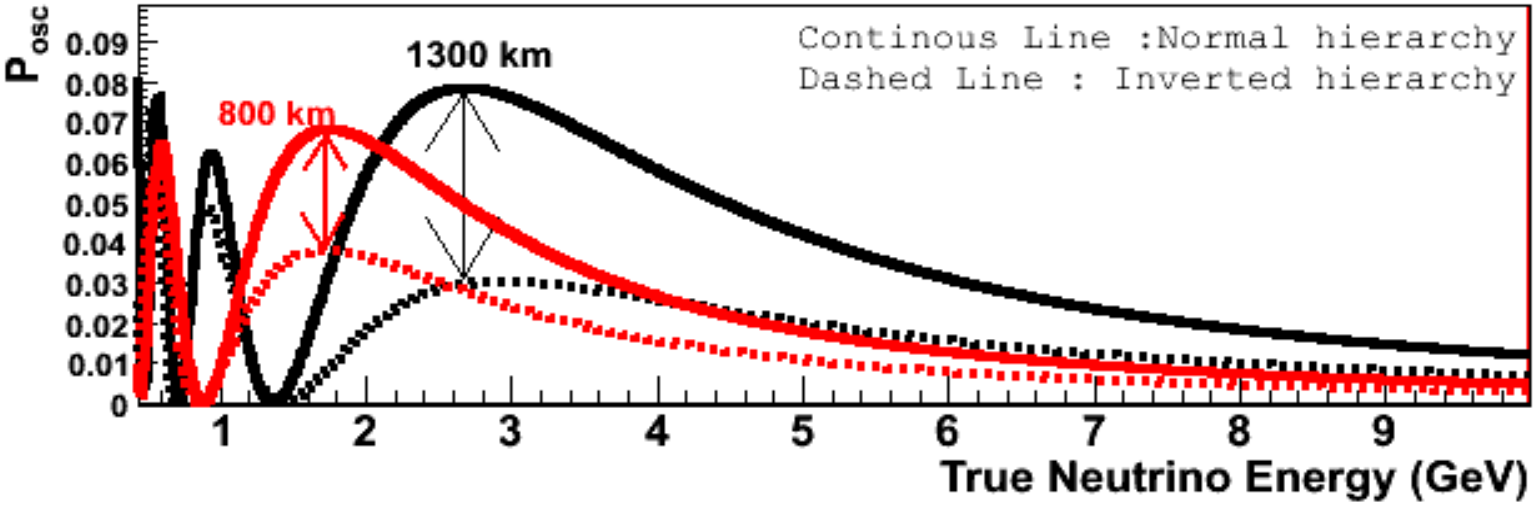
1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter adds a coherent forward scattering amplitude to neutrino oscillation amplitudes. This acts as a refractive index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum. For $P_{osc} = P(\nu_\mu \rightarrow \nu_e)$:





With longer baselines we can use accel ν to resolve sign(Δm^2_{31}).

The K2K experiment

The first 2 detector long baseline accel. ν expt.

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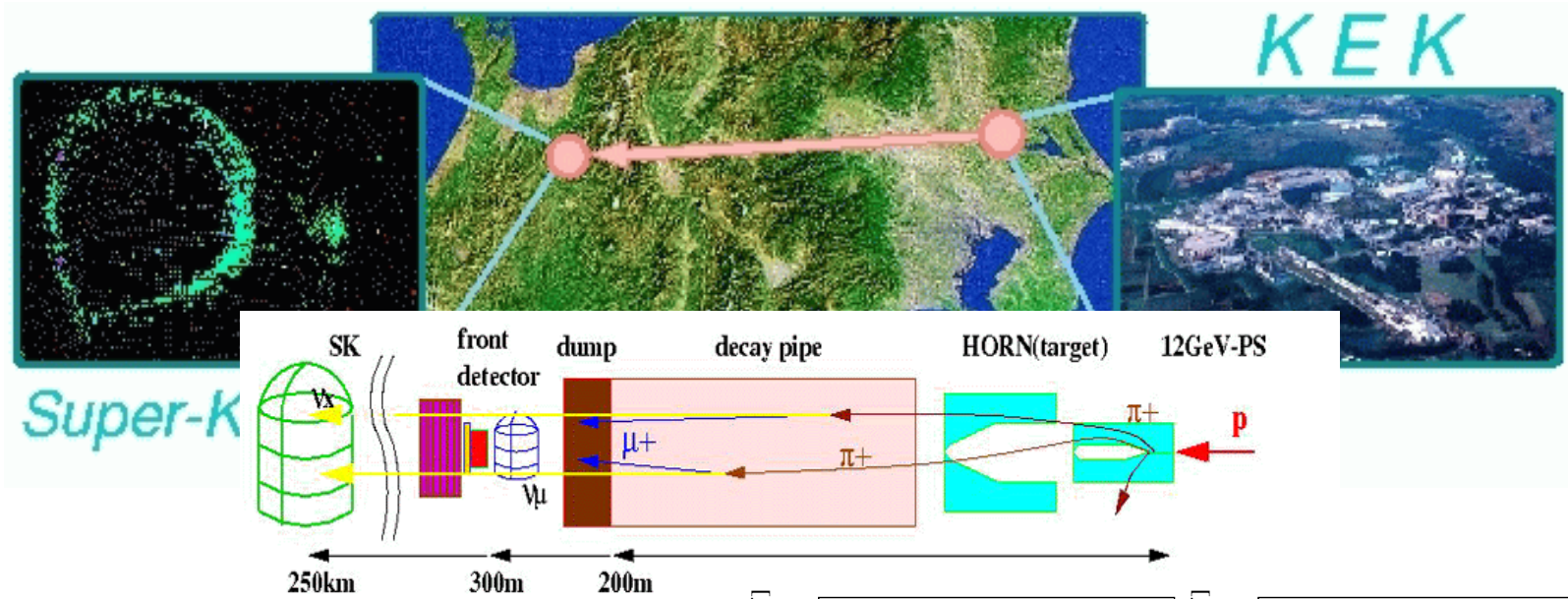
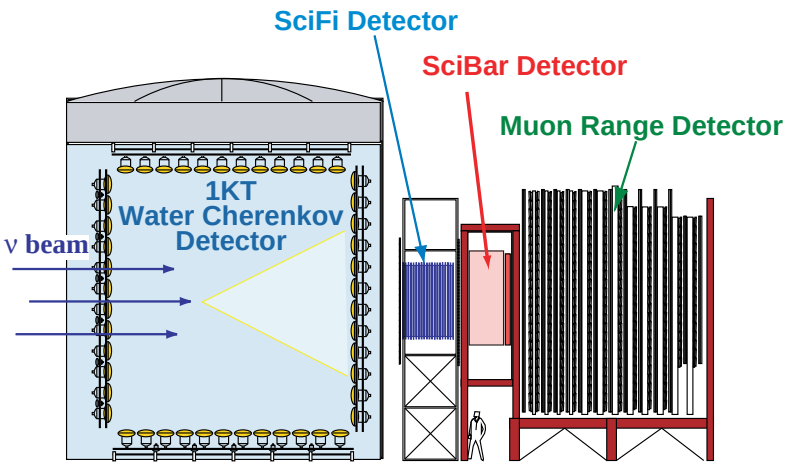
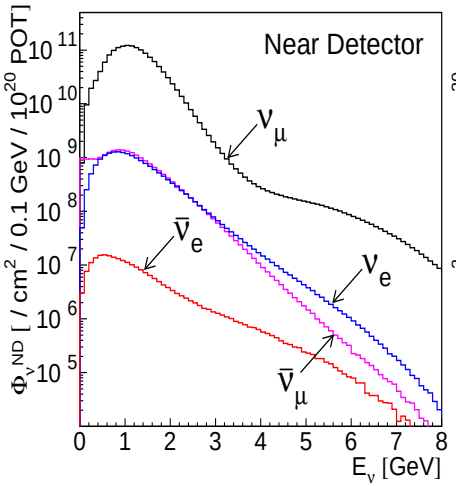
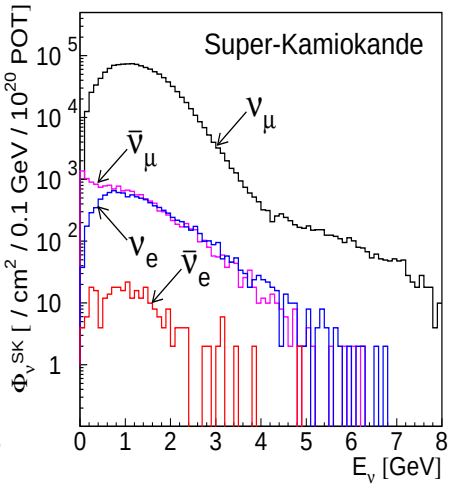
Confirm the SK oscillation result using ν_μ beam from KEK. **L = 250 km**.









K2K results: Accelerator ν_μ Disappearance

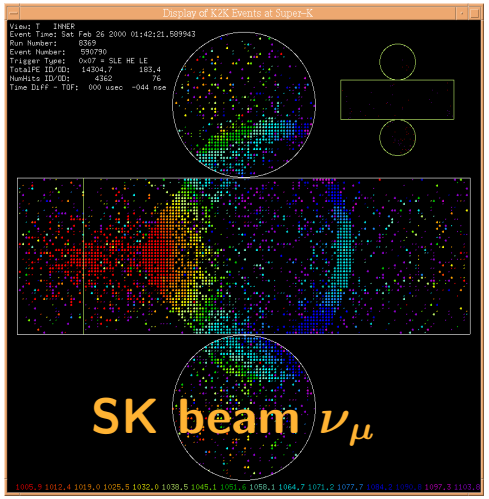
$2 \leftrightarrow 3$ mixing

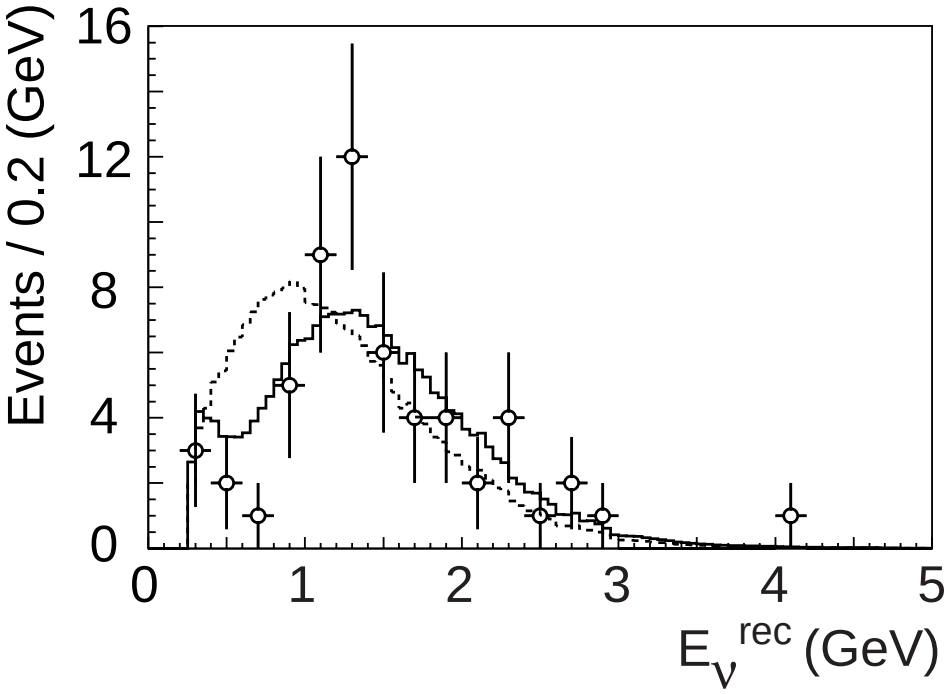
2005: *"Evidence for muon neutrino oscillation in an accelerator-based experiment" PRL 94 (2005) 081802*

Results: **Using 8.9×10^{19} protons-on-target.**

Find 107 ν_μ CC events in SK

Expected 151^{+12}_{-10}(syst) no-osc.



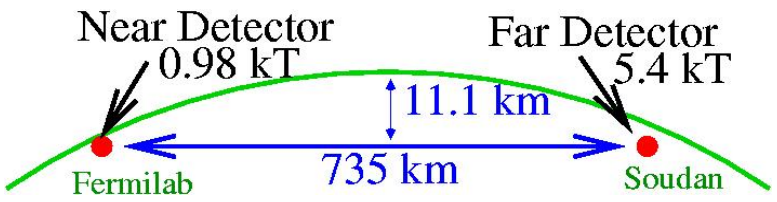


$\Leftarrow$ first evidence for accel. ν_μ disappearance

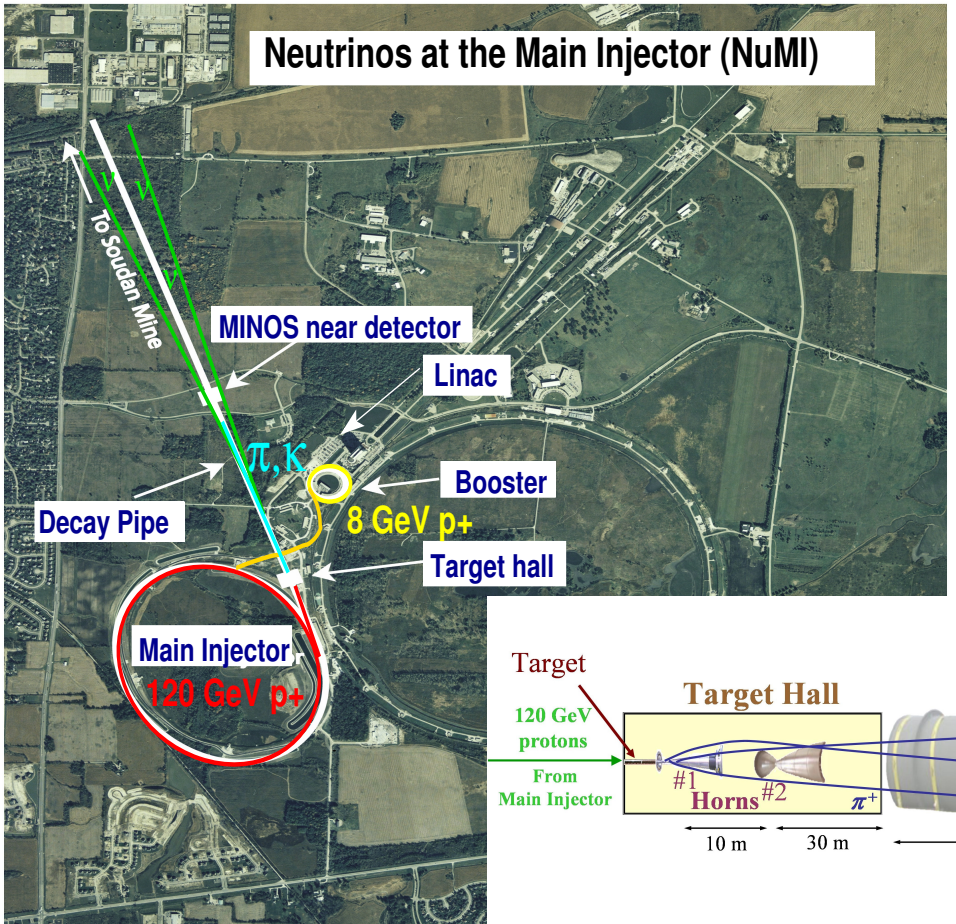
STATE-OF-THE-ART NEUTRINO ACCELERATOR EXPERIMENTS.

The NuMI/MINOS Accelerator ν_μ Experiment

The longest baseline accel. ν expt in operation. Average power = 320 kW.

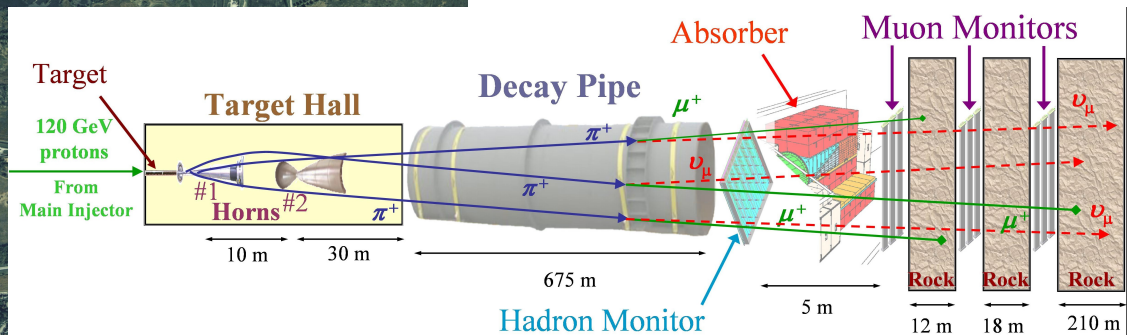


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



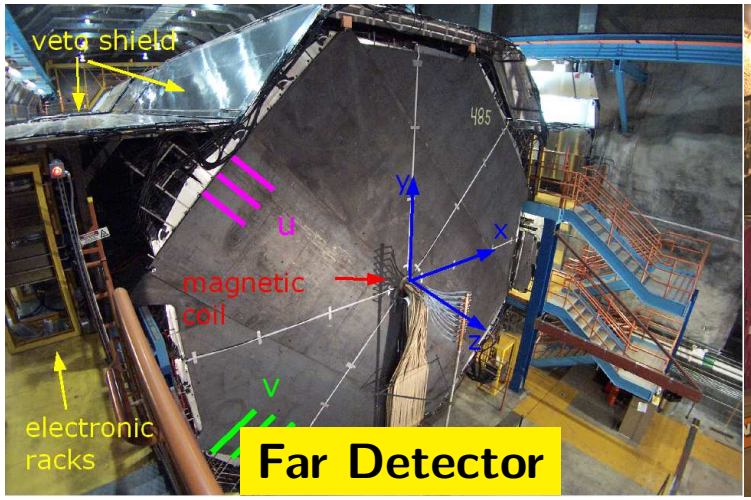
NuMI Horn 2 inner conductor
Radial field, B $\propto$ 1/r

3T at 200 kA



The MINOS Detectors

Magnetized iron calorimeters with 2.54 cm thick Fe plates sandwiched with scintillator strips (1 cm thick, 4.1 cm wide) readout by WLS fiber.



- **484 octogonal steel and scintillator plates 8m wide, ⇒ 5.4kTon and 30 m in length.**
- **Toroidal B-field, 1.3 T at r = 2m**
- **Cosmic μ veto shield**

- **282 "squashed" octagonal steel plates, 153 scintillator planes. ⇒ 1kTon and 16 m in length.**
- **Toroidal B-field, 1.3 T at r = 2m**

MINOS Results - 2009 (3.5×10^{20} protons-on-target)

The NuMI beam contains 91.5% ν_μ, 7 % $\bar{\nu}_\mu$ and 1.5% $\nu_e + \bar{\nu}_e$

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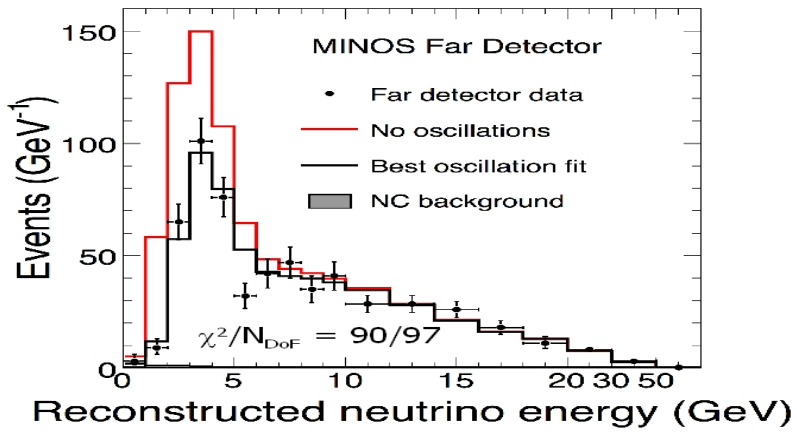
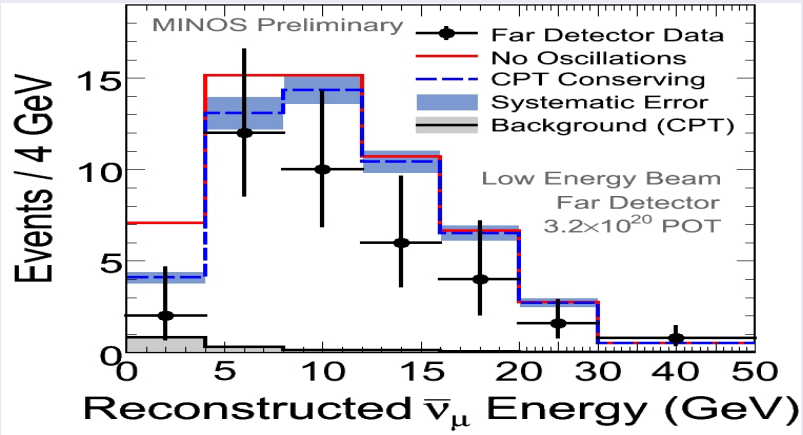
ν_μ disappearance

PRL 101, 2008



Expected no-osc 1065 ± 60.
Observe 848.

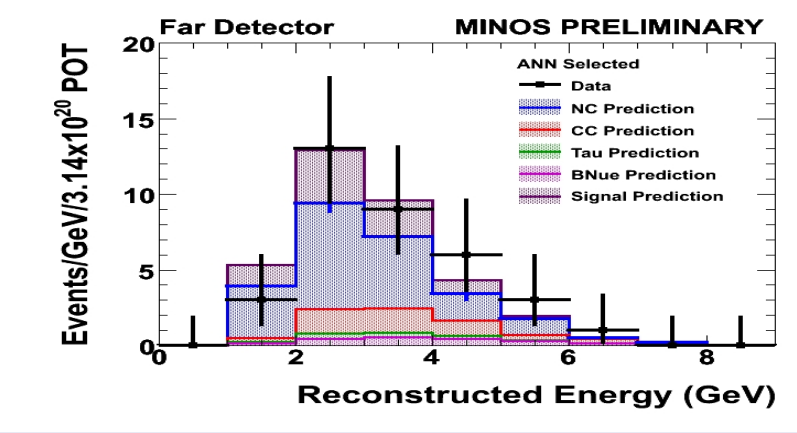
$\bar{\nu}_\mu$ disappearance



Expected (with osc) $58.3 \pm 7.6_{stat} \pm 3.6_{sys}$.
Observe 42.

ν_e appearance

PRL 103, 2009



Expected FD background: $27 \pm 5_{stat} \pm 2_{sys}$.
Observe 35.

MINOS results 2009:

ν_μ Disappearance:

$\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3} eV^2$ **5% accuracy**

$\sin^2 2\theta_{23} > 0.90(90\%C.L.)$

$\bar{\nu}_\mu$ Disappearance:

Fraction $\nu_\mu \rightarrow \bar{\nu}_\mu < 0.026(90\%C.L.)$

ν_e appearance:

$\sin^2 2\theta_{13} < 0.29(90\%C.L.); \Delta m^2 > 0, \delta_{cp} = 0$

$\sin^2 2\theta_{13} < 0.42(90\%C.L.); \Delta m^2 < 0, \delta_{cp} = 0$

Search for ν_s

MINOS Results - 2009 (3.5×10^{20} protons-on-target)

The NuMI beam contains 91.5% ν_μ, 7 % $\bar{\nu}_\mu$ and 1.5% $\nu_e + \bar{\nu}_e$

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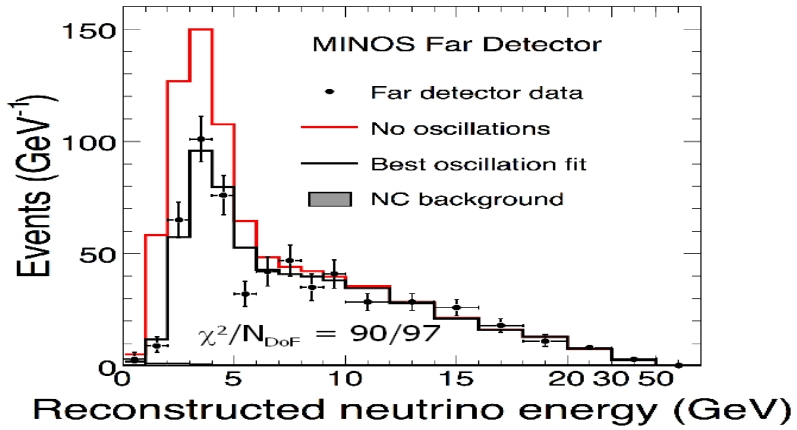
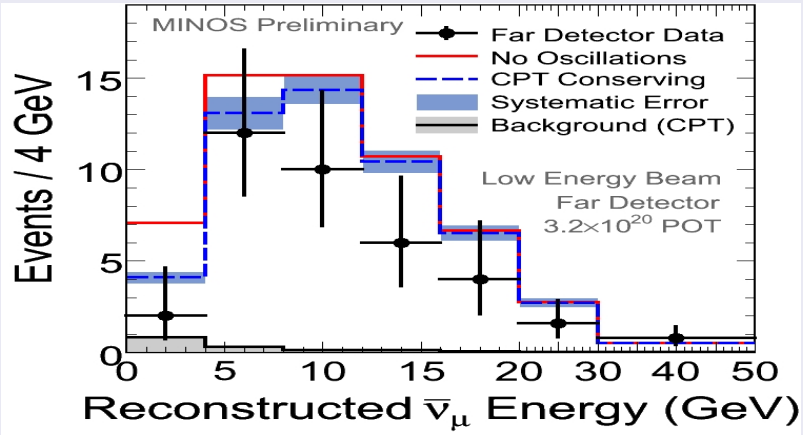
PRL 101, 2008



Expected no-osc 1065 $\pm$ 60.
Observe 848.

$\bar{\nu}_\mu$ disappearance



Expected (with osc) $58.3 \pm 7.6_{stat} \pm 3.6_{sys}$.
Observe 42.

Coming soon: ν_e appearance 2010

Expect 3σ sensitivity at $\sin^2 2\theta_{13} = 15\%$

Lisa Whitehead, BNL Colloquium 4/9/2010

MINOS results 2009:

ν_μ Disappearance:

$\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3} eV^2$ **5% accuracy**

$\sin^2 2\theta_{23} > 0.90(90\%C.L.)$

$\bar{\nu}_\mu$ Disappearance:

Fraction $\nu_\mu \rightarrow \bar{\nu}_\mu < 0.026(90\%C.L.)$

ν_e appearance:

$\sin^2 2\theta_{13} < 0.29(90\%C.L.); \Delta m^2 > 0, \delta_{cp} = 0$

$\sin^2 2\theta_{13} < 0.42(90\%C.L.); \Delta m^2 < 0, \delta_{cp} = 0$

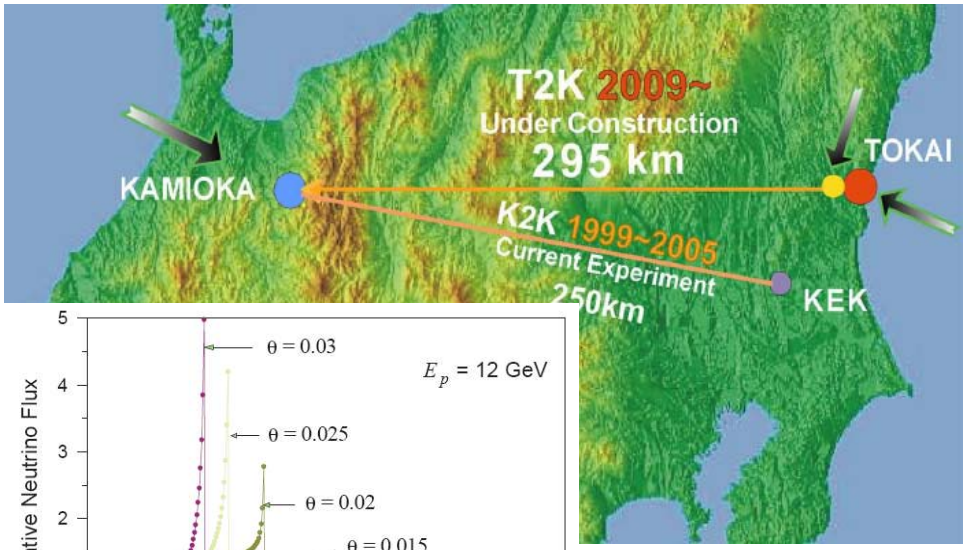
Search for ν_s

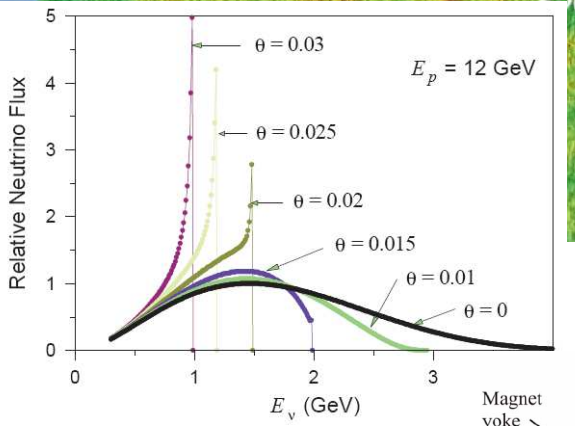
Off-axis high intensity ν_μ beams: T2K

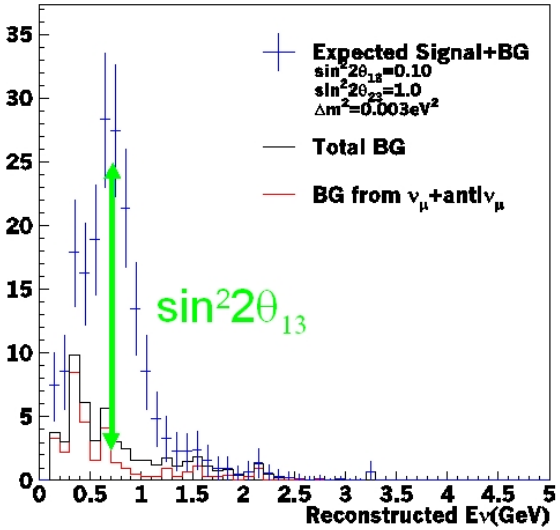
30-50 GeV p accel, designed for 750 kW, started operations 2009

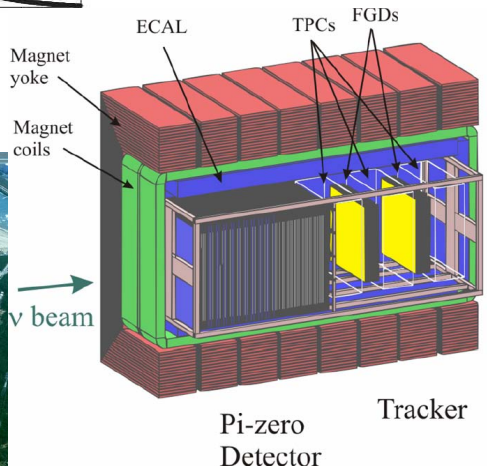
First proposed for BNL E-889 (1995): A narrow beam of ν_μ can be achieved by going off-axis to the π beam. Better S:B at oscillation max.

Expected ν_e appearance signal at $\sin^2 2\theta_{13} = 10\%$:





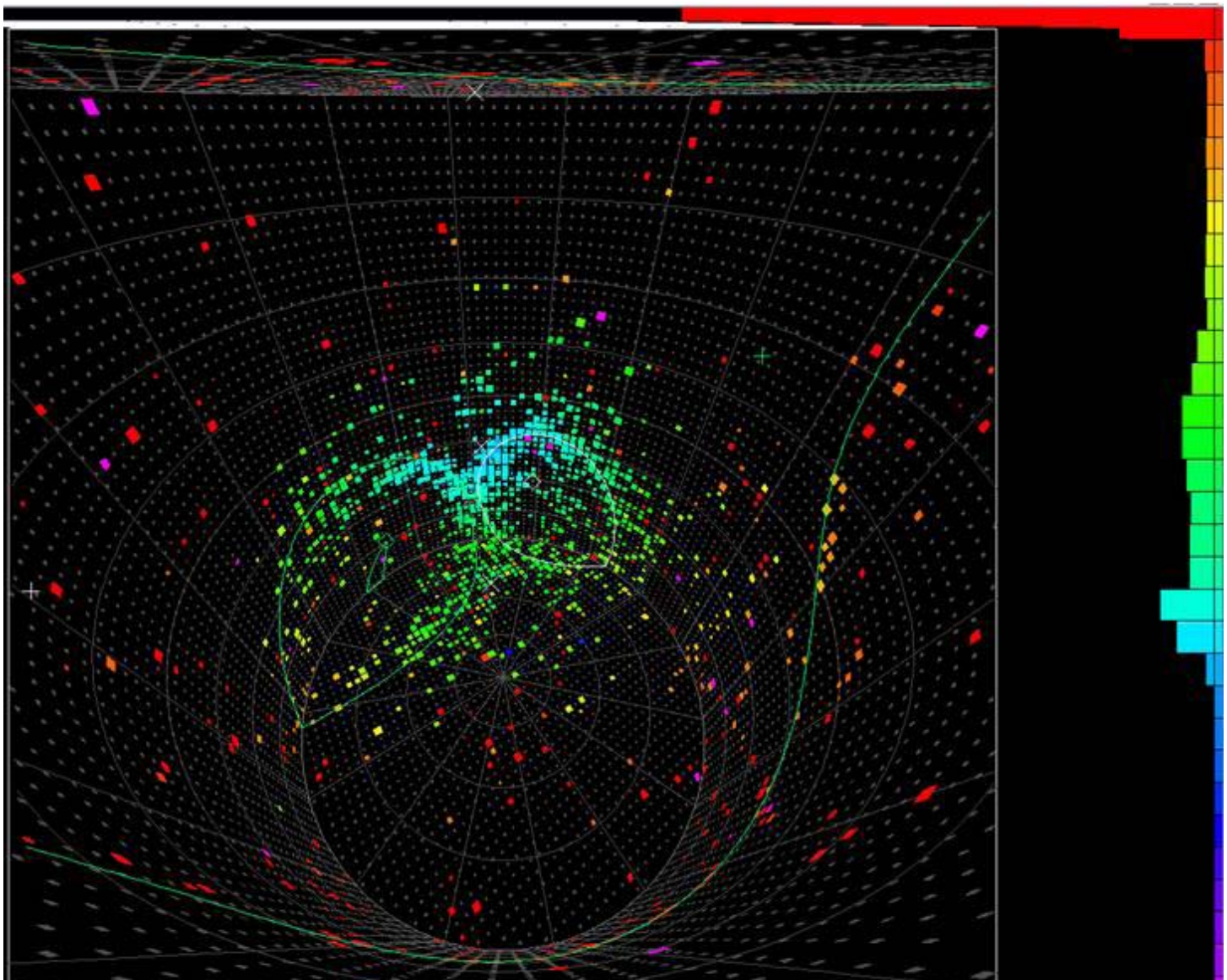




Goal: search for $\nu_\mu \rightarrow \nu_e$ with sensitivity to $\sin^2 2\theta_{13} \sim 1\%$

First T2K Neutrino Event

Feb 25, 2009: A CC ν_μ interaction which produced $\pi^0 \rightarrow \gamma\gamma$:



STATE-OF-THE-ART NEUTRINO REACTOR EXPERIMENTS.

Short Baseline Reactor $\bar{\nu}_e$ oscillations

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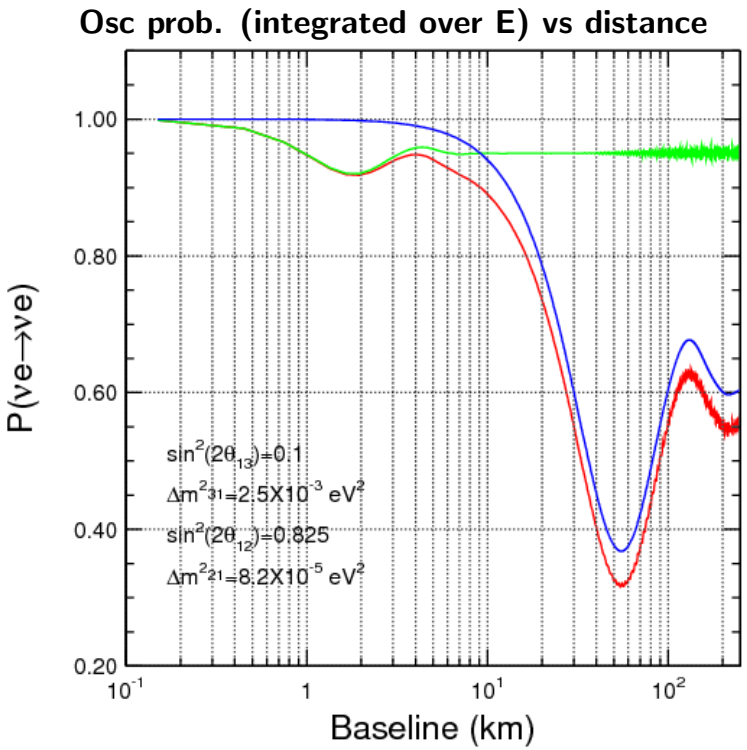
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$



Unambiguous measurement of $\sin^2 2\theta_{13}$

Getting to $\sin^2 2\theta_{13} < 0.01$

Lots of statistics: -Powerful nuclear reactors + more massive detectors

Supress cosmic backgrounds:
-Increase overburden = go deeper underground.

Reduce systematic uncertainties:
-Deploy near detectors as close as possible to reactor to minimize reactor flux uncertainties.
-Use "identical" N/F detectors to reduce near/far detector uncertainties.
-Calibration, calibration, calibration...

Detecting $\bar{\nu}_e$ using GD-loaded LS.

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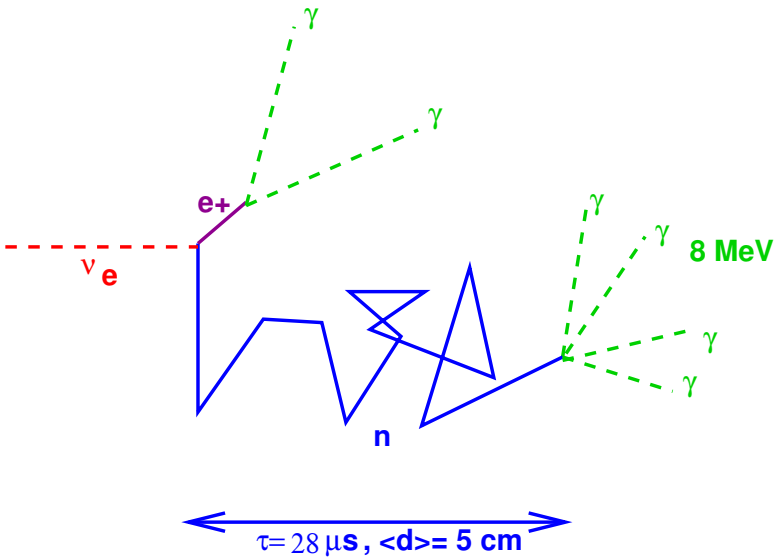
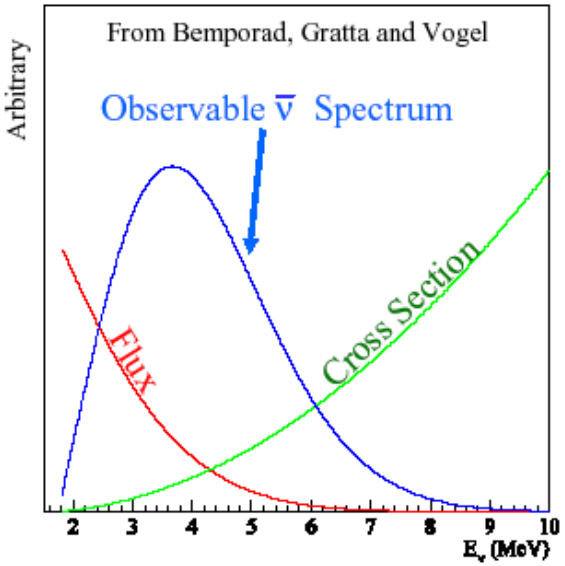
The active target in each detector module is liquid scintillator loaded with 0.1% Gd





The detection sequence is as follows: $\bar{\nu}_e + p \rightarrow n + e^+$ **THEN**

$e^+ + e^- \rightarrow \gamma\gamma$ **(2X 0.511 MeV +**T_{e^+}**, prompt)**

$n + p \rightarrow D + \gamma$ **(2.2 MeV,** $\tau \sim 180\mu s$**,** $\sigma = 0.3b$**). OR**

$n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$**'s (8 MeV,** $\tau \sim 28\mu s$**,** $\sigma = 5 \times 10^4 b$**).**

⇒ delayed co-incidence of e^+ **conversion and n-capture (> 6 MeV)**

with a specfic energy signature

The Daya Bay Reactor Complex

Reactor Specs:

Located 55km north-east of Hong Kong.

Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW_{th}

By 2011: 2 more cores at Ling Ao II site = 17.4 GW_{th} $\Rightarrow$ top five worldwide

1 $GW_{th} = 2 \times 10^{20} \bar{\nu}_e$/second

Deploy multiple near and far detectors

Reactor power uncertainties $< 0.1\%$

The Daya Bay Experiment

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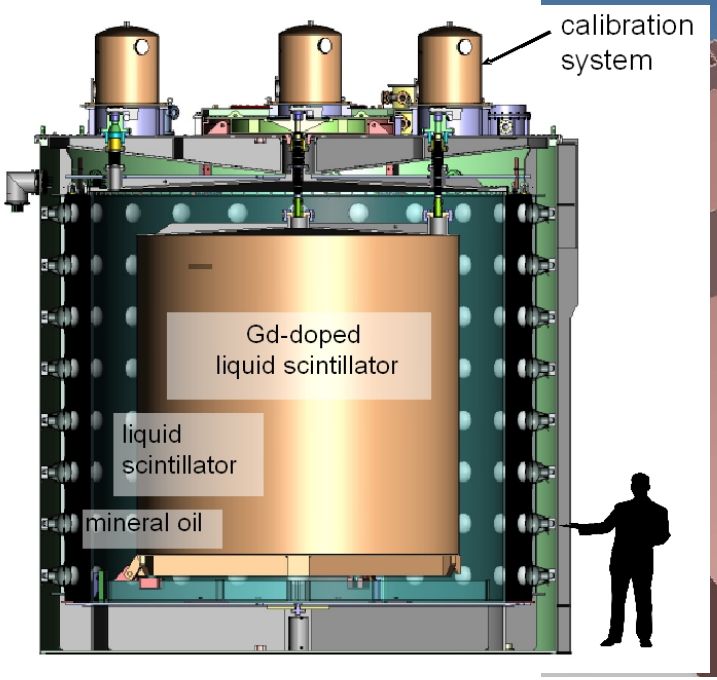

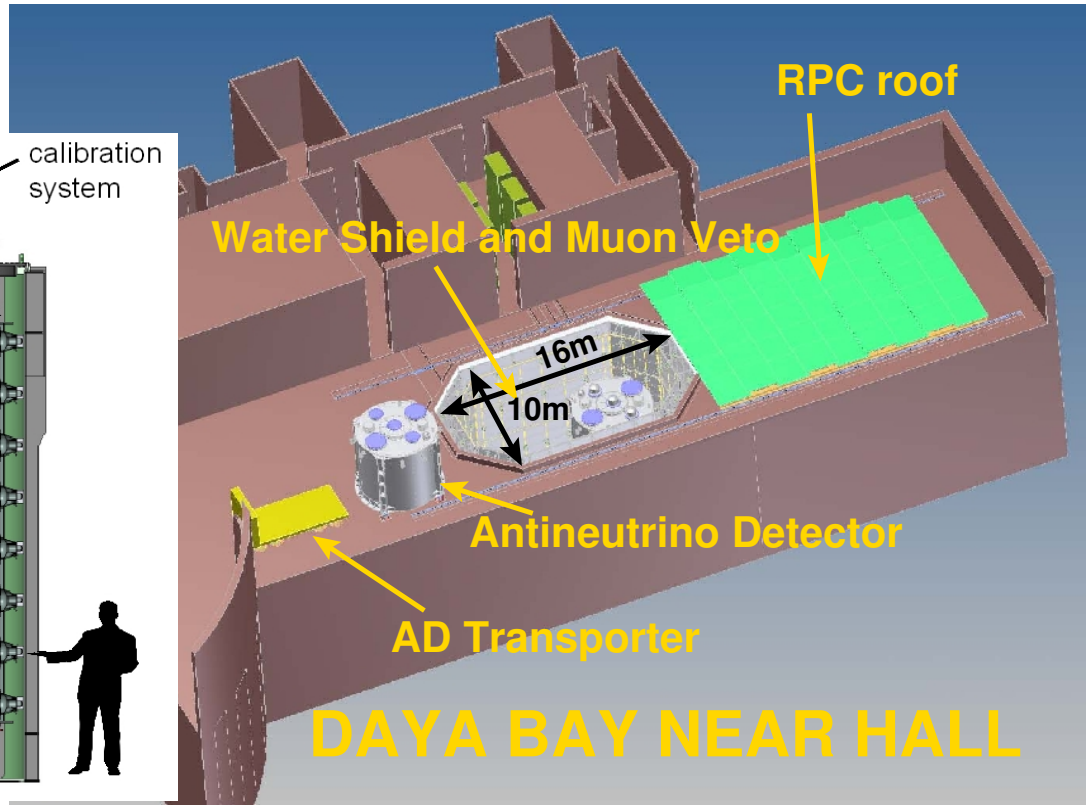

- **Multiple "identical" detectors at each site.**
- **Manual and multiple automated calibration systems per detector.**
- **Thick water shield to reduce cosmogenic and radiation bkgds.**

	DYB	LA	Far
Event rates/20T/day	840	740	90

Daya Bay Sensitivity

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)	Strategy
# protons	H/C ratio	0.8	< 0.1	Fill in pairs/calib
	Mass	-	< 0.3	Load cells and mass flowmeters
Detector Efficiency	Energy cuts	0.8	0.2	lower threshold/calib
	Position cuts	0.32	0.0	3-zone
	Time cuts	0.4	0.1	Common clock $\sim$ 10ns
	H/Gd ratio	1.0	0.1	fill in pairs/calib
	n multiplicity	0.5	0.05	Deeper/muon veto
	Trigger	0	0.01	Redundant triggers
	Live time	0	< 0.01	Common GPS clock
Total detector-related uncertainty		1.7%	0.38%	

End 2010: Near detector ready. End 2011: far detectors ready

Reach sensitivity to $\sin^2 2\theta_{13} < 0.01$ @ 90% C.L. by 2014

θ_{13} by 2016

M. Mezzetto, arXiv:0905.2842

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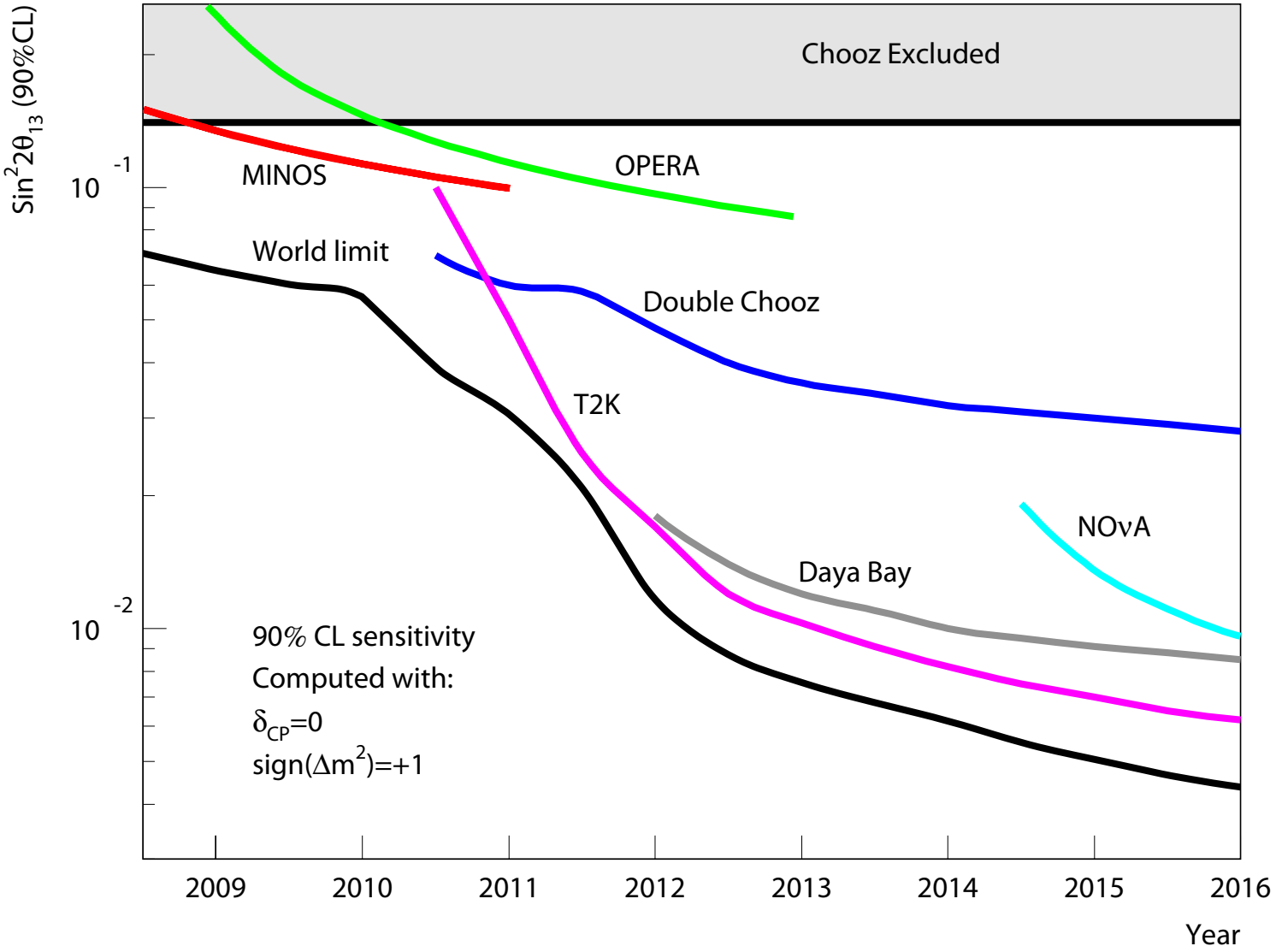

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THE HUNT FOR ν CHARGE-PARITY VIOLATION

CP Violation with long baseline accel. experiments

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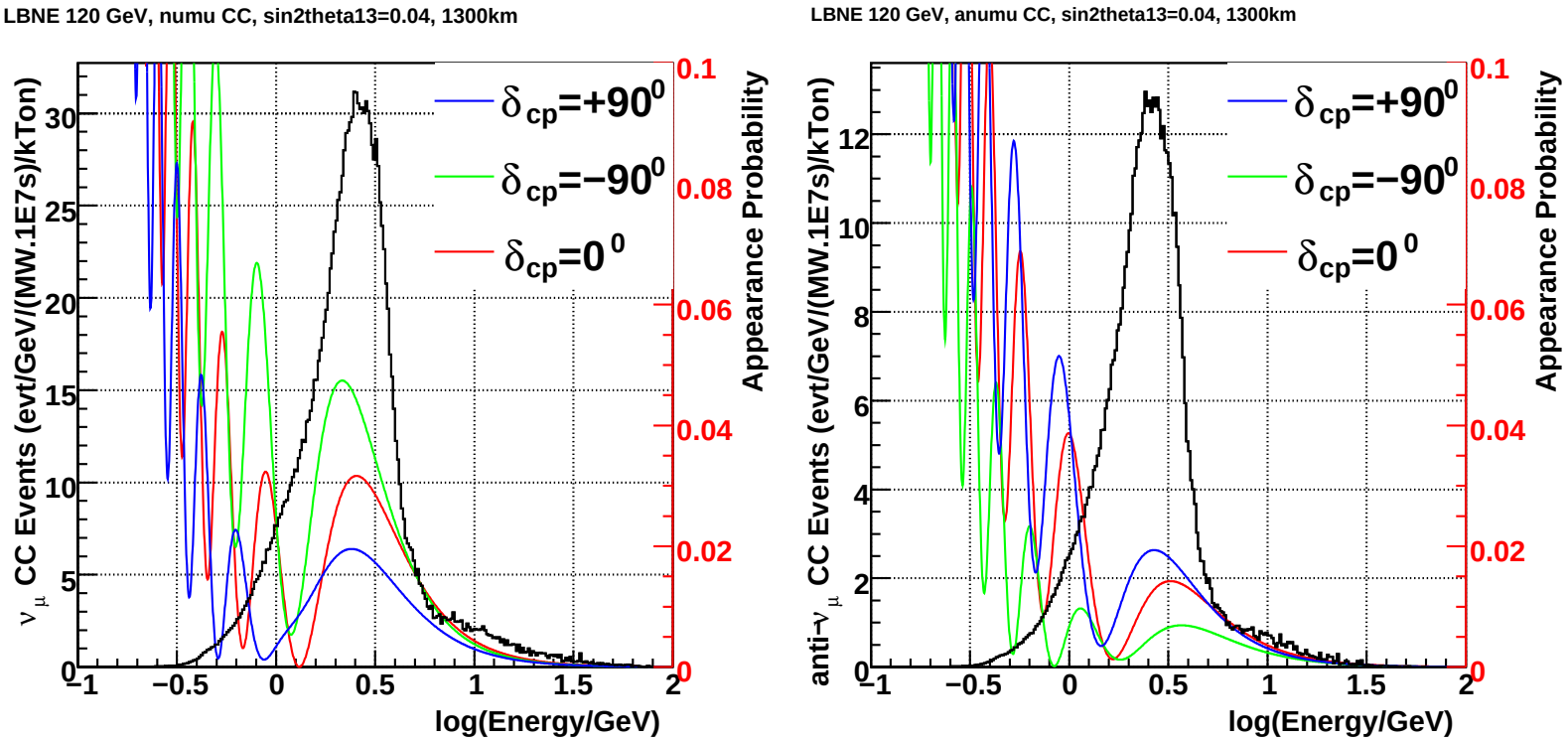
Appearance probabilities of $\nu_\mu \longrightarrow \nu_e$ for different values of the CP phase.
A CP phase $\neq 0, \pi$ implies charge-parity is violated in the lepton sector.

Normal Hierarchy ($\Delta m^2_{31} > 0$)

ν $\bar{\nu}$



CP effects largest $E_\nu < 3$ GeV.

Need high power wide-band beams with ν and $\bar{\nu}$ to resolve degenercies

CP Violation with long baseline accel. experiments

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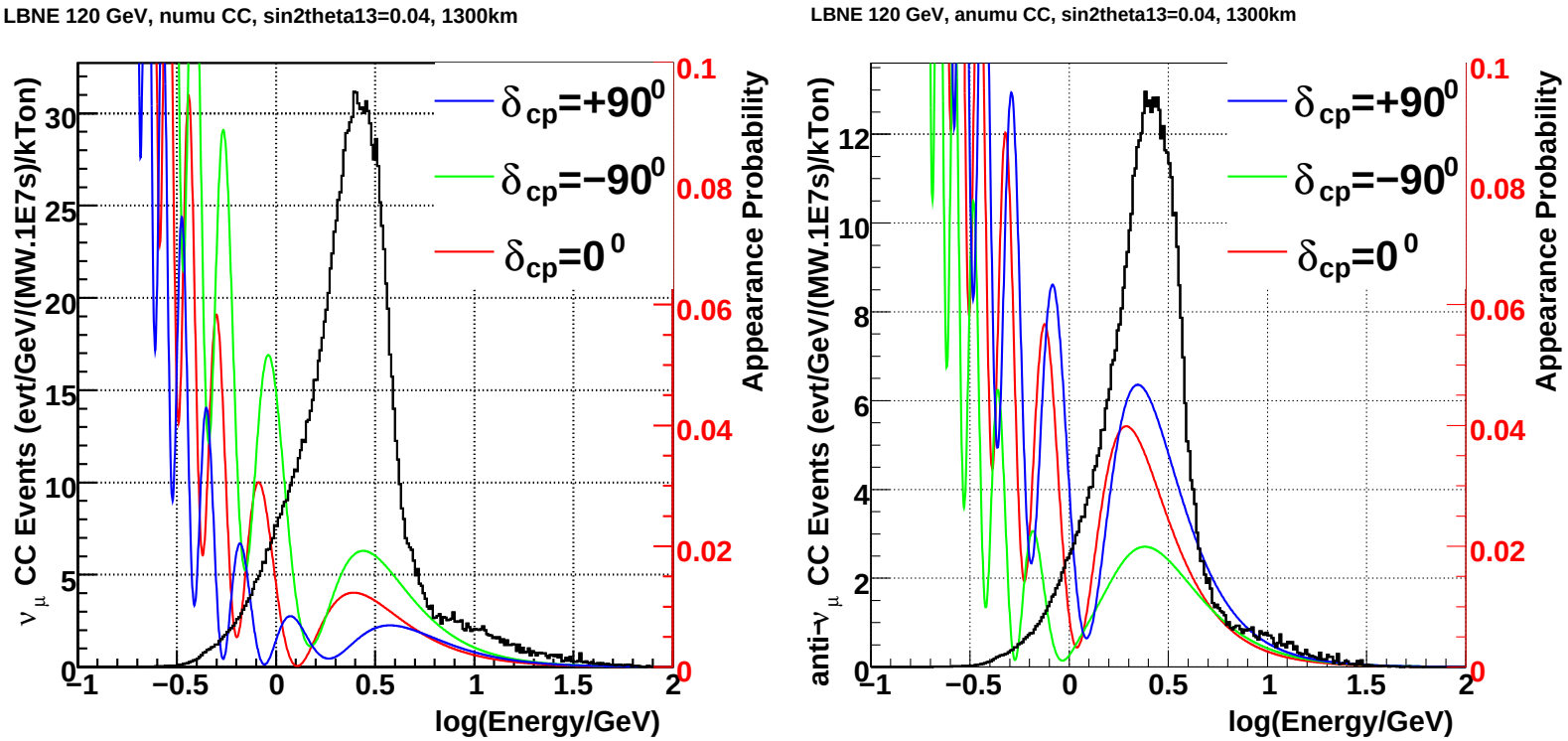
Appearance probabilities of $\nu_\mu \longrightarrow \nu_e$ for different values of the CP phase.
A CP phase $\neq 0, \pi$ implies charge-parity is violated in the lepton sector.

Reversed Hierarchy ($\Delta m^2_{31} < 0$)

ν $\bar{\nu}$

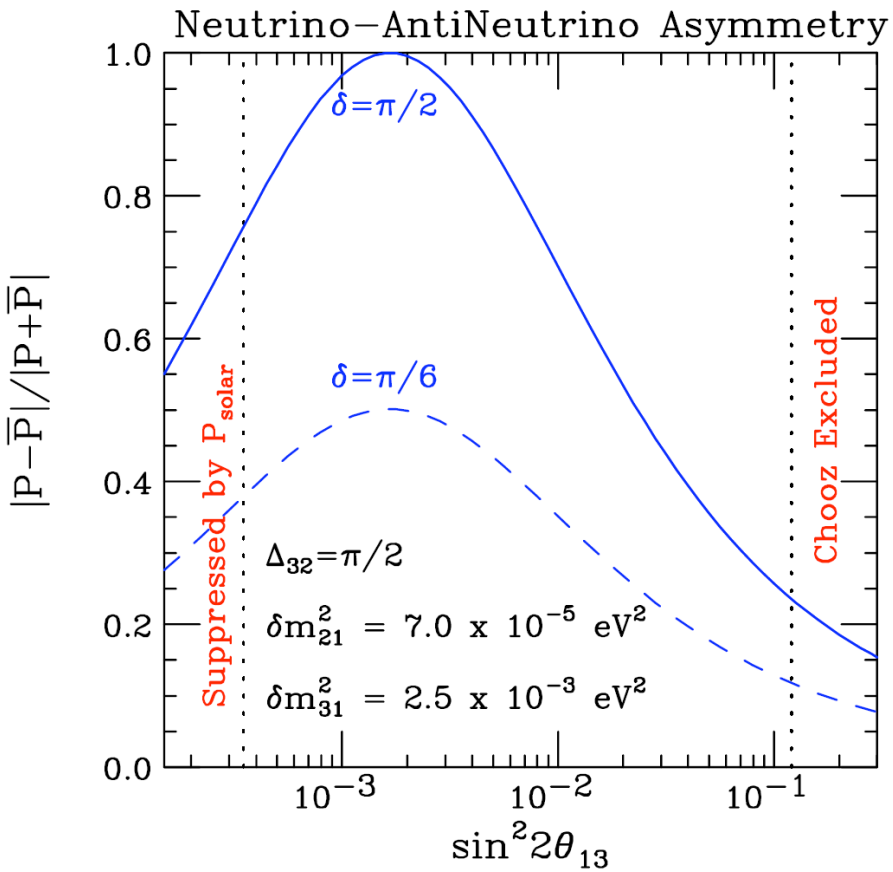


Matter effects large $E_\nu > 1.5$ GeV.

Need high power wide-band beams with ν and $\bar{\nu}$ to resolve degenercies

θ_{13} and CPV

Asymmetry in $\mathrm{P}(\nu_\mu \rightarrow \nu_e)$ and $\bar{\mathrm{P}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs $\sin^2 2\theta_{13}$:

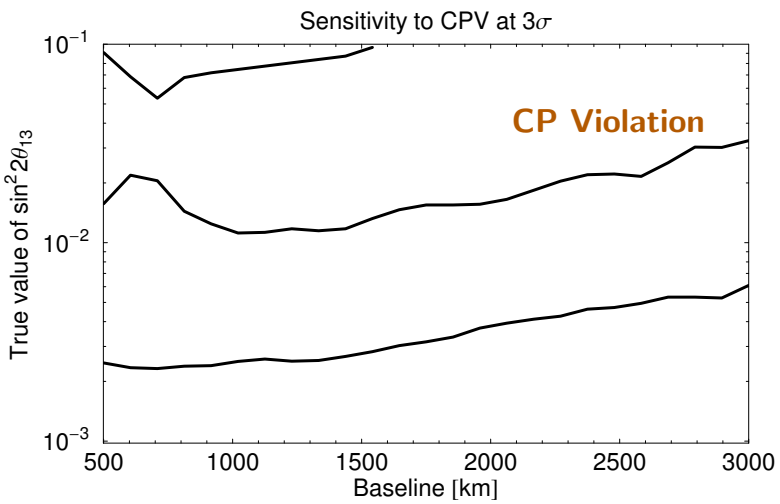


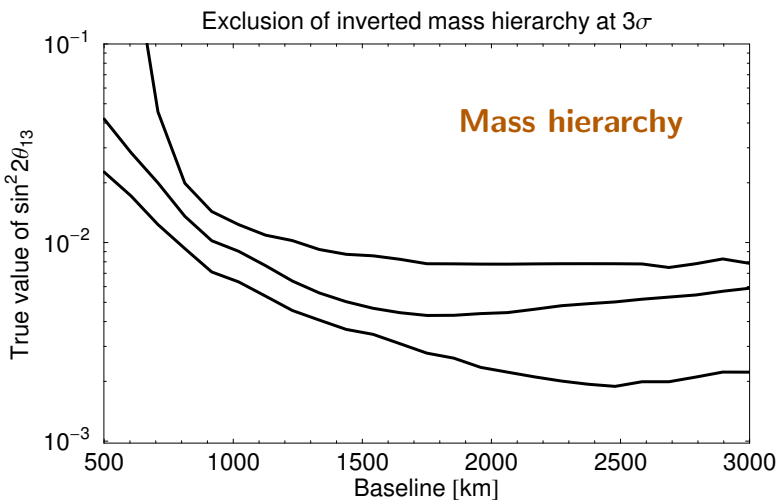
For values of $\sin^2 2\theta_{13} > 0.002$:

the CP asymmetry increases with *smaller* θ_{13}

Physics sensitivity vs baseline

Using a broad-band beam with a peak interaction rate at 2 GeV, FWHM=3 GeV, a parameterized water Cerenkov detector and exposure of 5MW.yr (ν) + 10 MW.yr ($\bar{\nu}$) (V. Barger *et al.*. Phys. Rev. D 74, 073004 2006)**:**





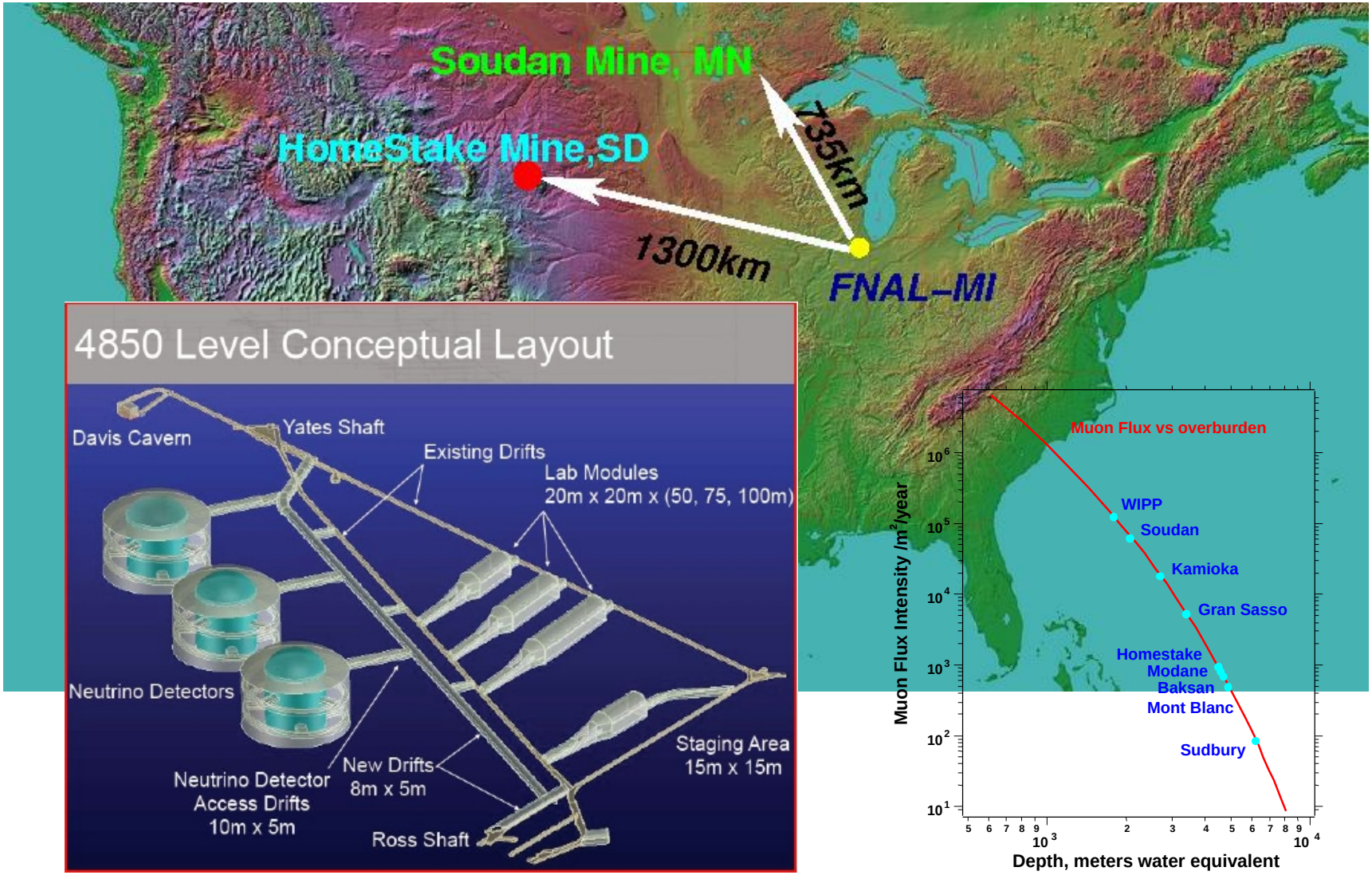
Minimum value of $\sin^2(2\theta_{13})$ for which the sensitivity is $> 3\sigma$ for (best,50%, worst) of δ_{cp} values

Longer baselines = larger mass effects

Best sensitivity is for baselines 1200 - 2500km

The Long Baseline Neutrino Experiment

A Long Baseline Neutrino Experiment (LBNE) from Fermilab to megaton scale detectors at Homestake is now being designed. CDR late 2010.



Fermilab Neutrino Beams: Future

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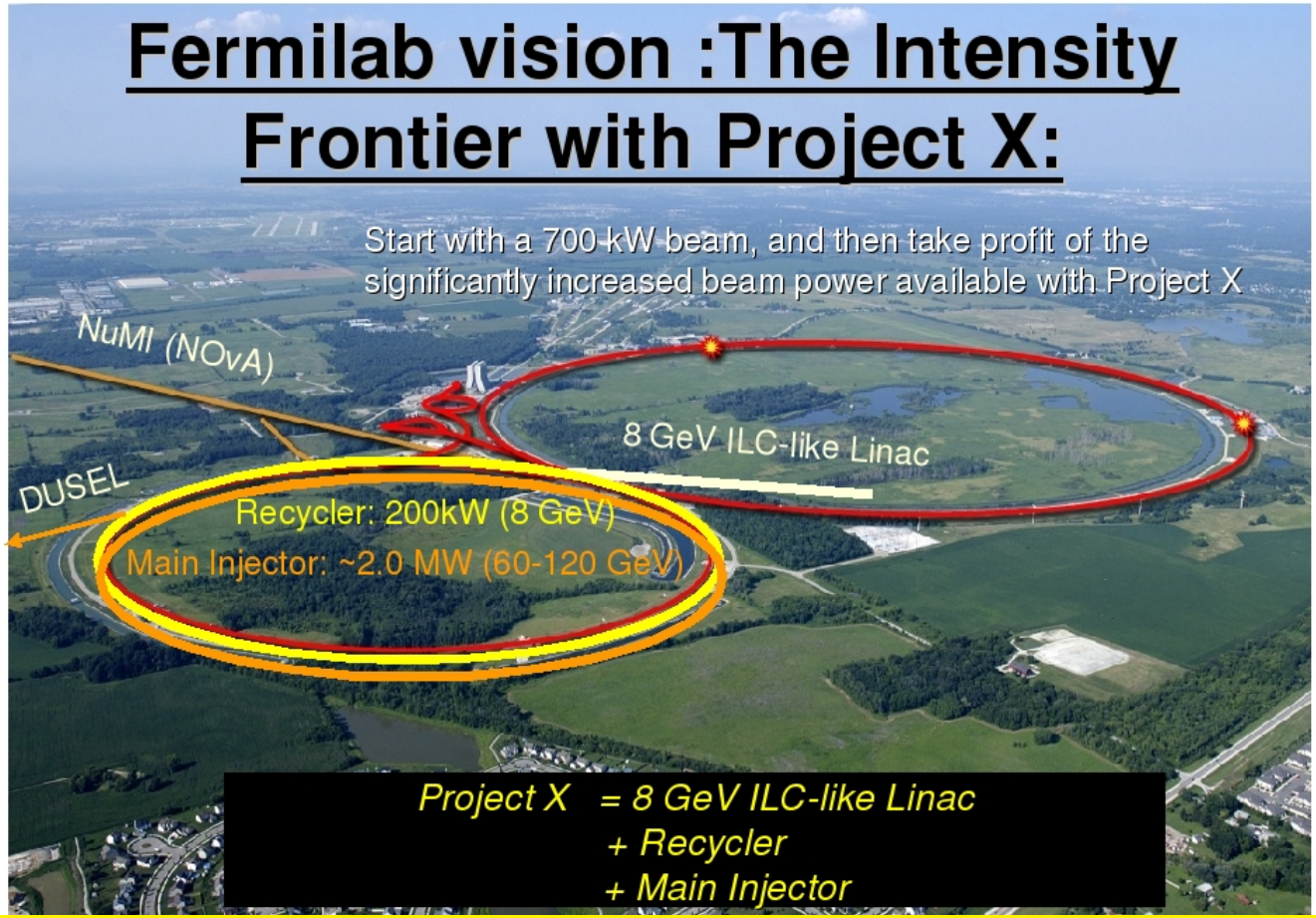
The NuMI beamline uses a 300kW proton beam from the Main Injector (700 kW by 2012).

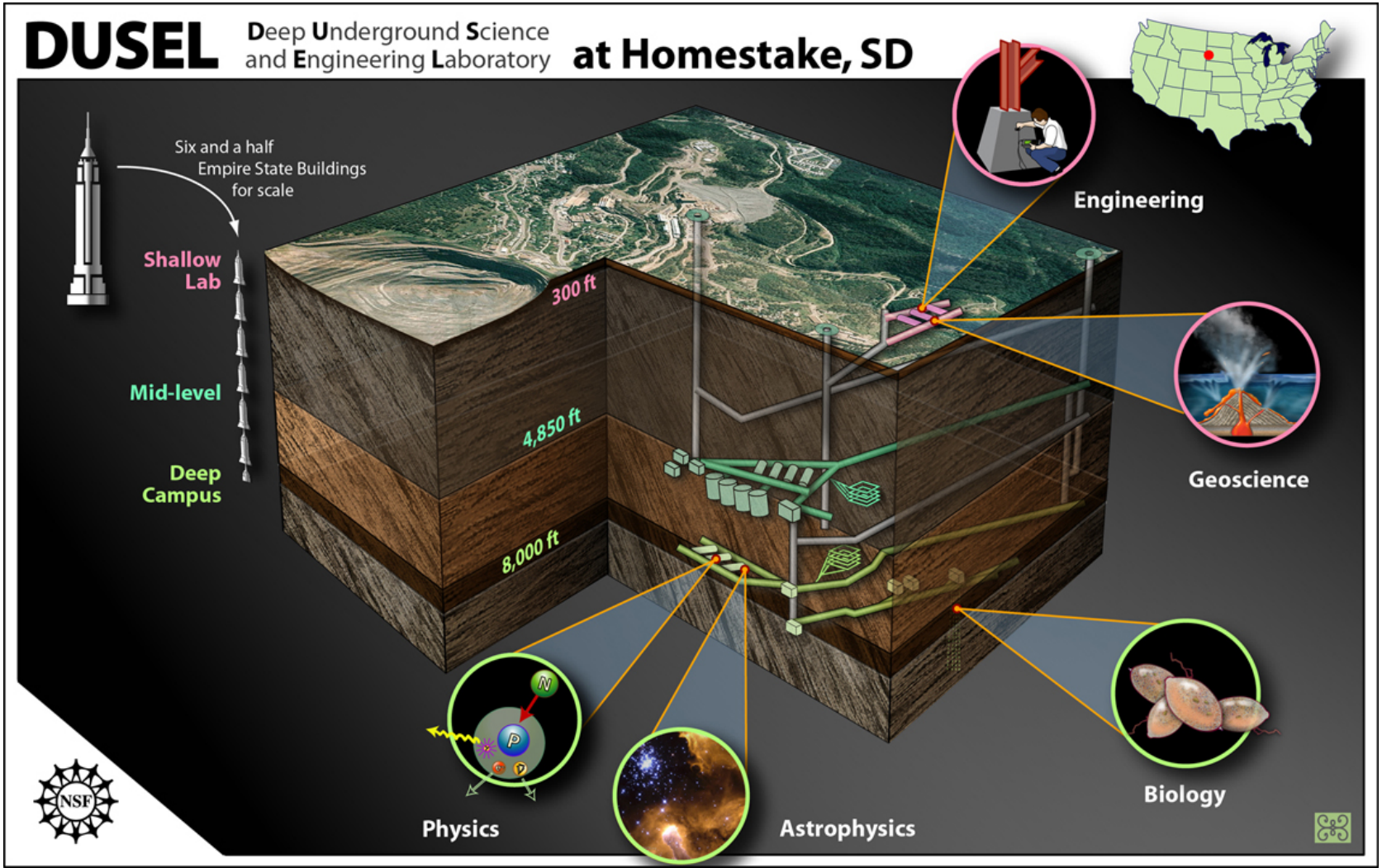
NuMI is the most powerful ν beamline operating today.



The proposed Project X at FNAL $\longrightarrow$ 2MW with $E_p = 60 - 120$GeV

Deep Underground Science and Engineering Laboratory

July 10, 2007: the National Science Foundation (NSF) selected the University California-Berkeley to produce a techincal design for DUSEL at Homestake Mine, SD



DUSEL Timeline

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DUSEL Working Timeline

- July '08: Internal project review of facility & infrastructure.
- January '09: NSF Project Review #1.
- January '10: NSF Project Review #2.
- December '10: NSF Preliminary Design Review (PDR).
  - Project readiness, plan will be assessed at this milestone.
- Spring '11: Presentation of DUSEL MREFC package to NSB.
- FY13: Earliest construction funding (MREFC) start, if approved.

Planning with potential partners (DOE, international, etc.) being integrated into above schedule.

The LBNE Collaboration

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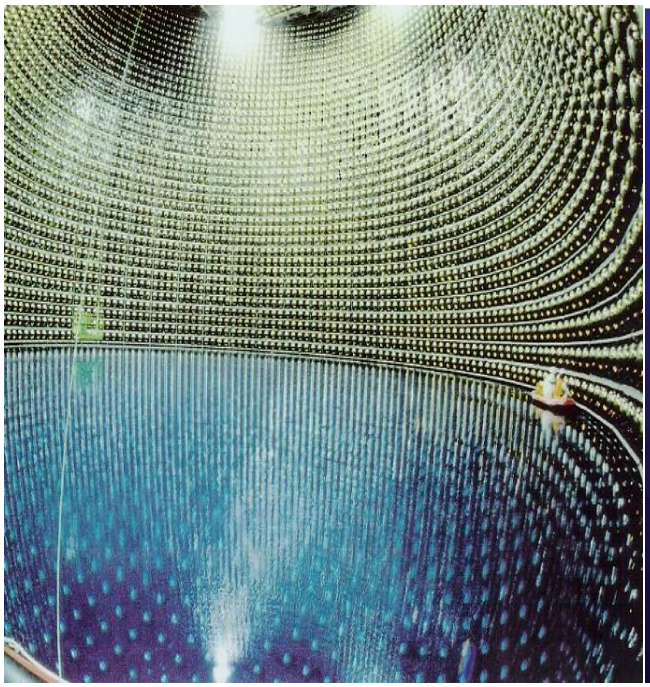
Institutions: ANL, Boston, BNL, Caltech, UC Davis, UC Irvine, UCLA, Chicago, Colorado State, Columbia, Drexel, Duke, FNAL, Indiana, INFN(Catania), Kansas State, LANL, LLNL, LBL, LSU, Maryland, MIT, Minnesota, Minnesota (Duluth), Penn, Princeton, RPI, S. Carolina, Tennessee, Texas, Tufts, Wisconsin, Yale

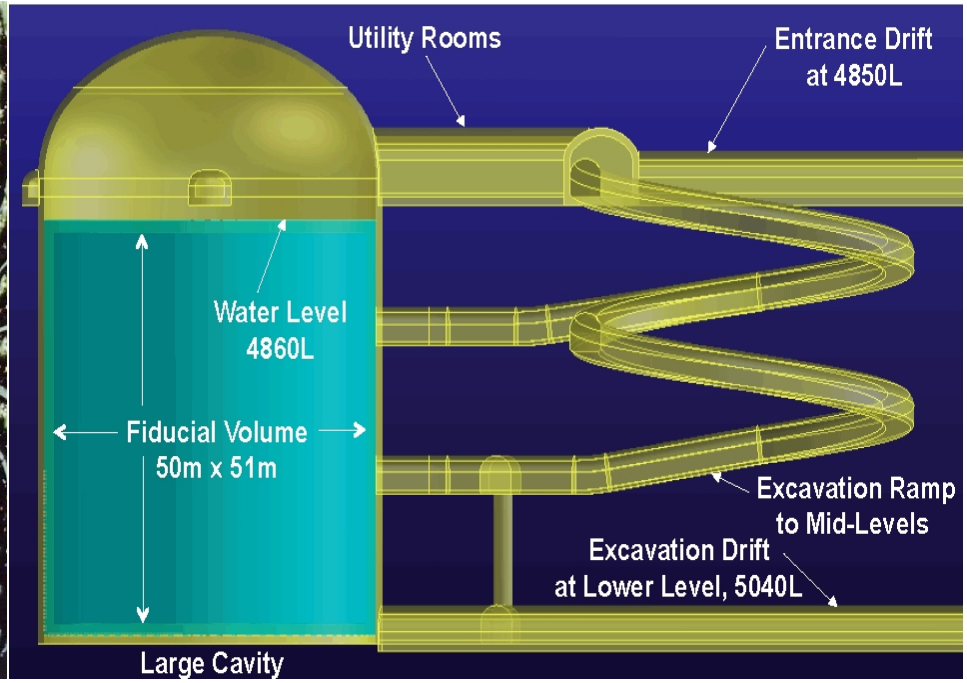
Collaboration meeting 2/26-2/28, 2009 at UC Davis, CA

DUSEL Detectors: Water Cerenkov

SuperKamiokande : 50kT



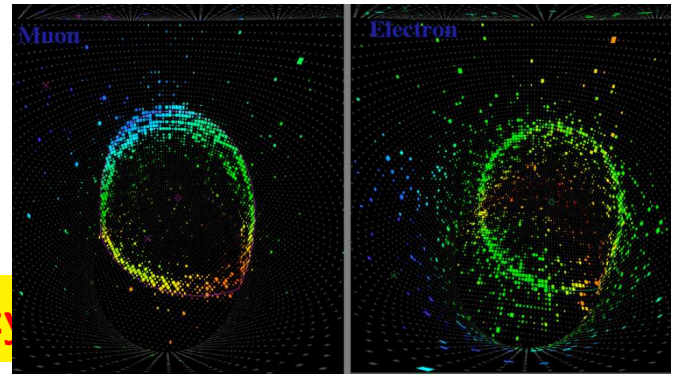
DUSEL WCe Module : $\sim$ 120 kT



3 100kT (fiducial) modules, $\approx$ 55m diameter, $\approx$ 60m height, 60K 10" PMTs/module (25% coverage)

Known technology 3 – 4$\times$ SuperK

Large NC pi^0 backgrounds, low efficiency



DUSEL Detectors: Liquid Argon TPC

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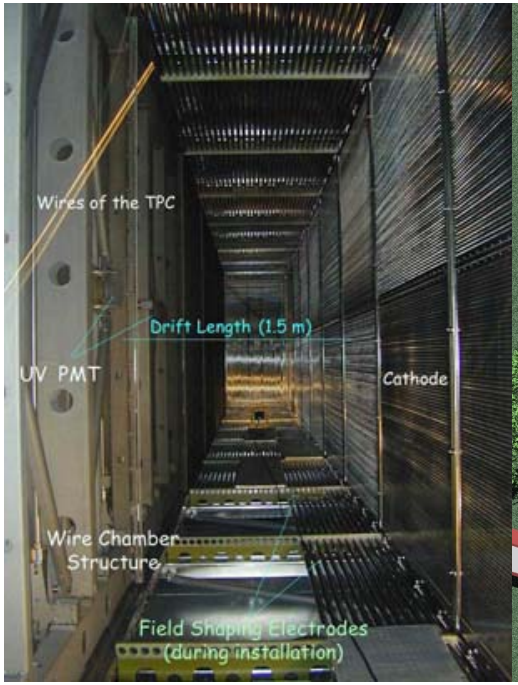
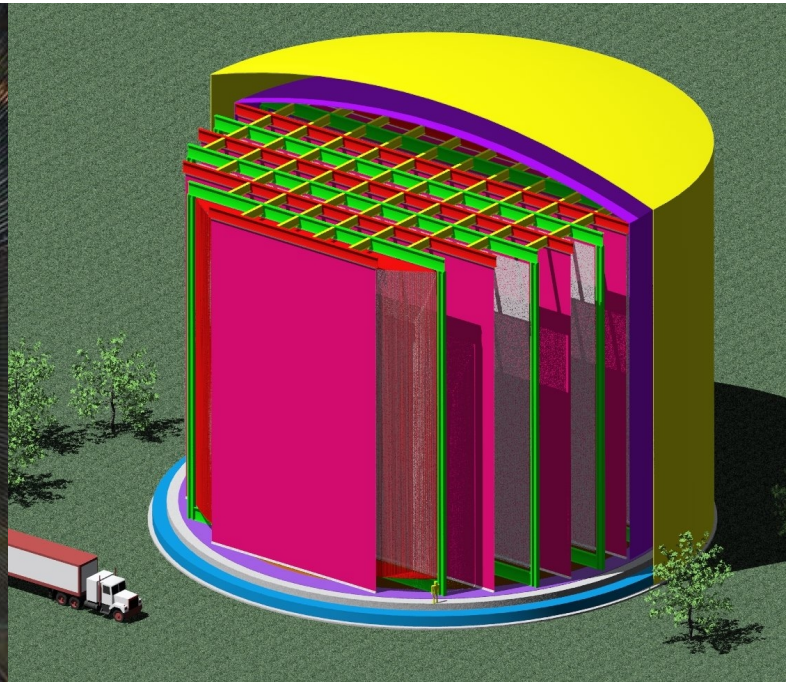
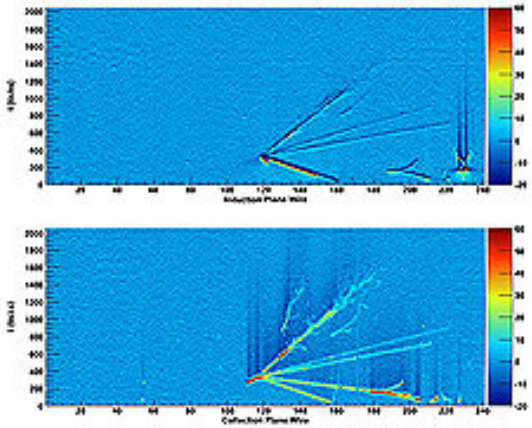
ICARUS module : 0.3kT



DUSEL LAr : 50 kT



ArgoNeuT (175 litre) prototype in the NuMI beam →



High efficiency and purity

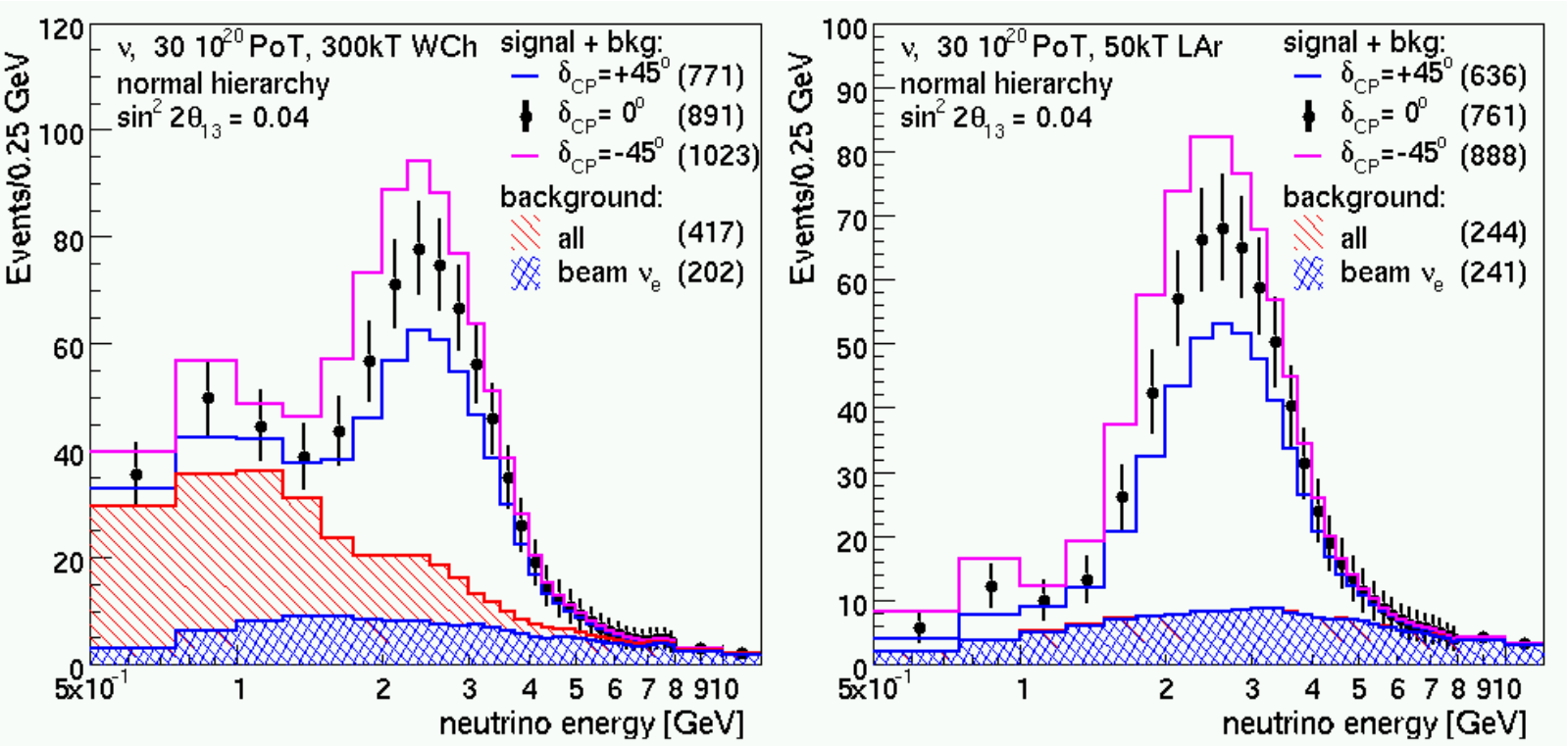
Requires 100× scale-up - unproven.

LBNE/DUSEL spectra and event rates

A preliminary on-axis wide-band beam for LBNE based on the NuMI focusing system has been developed. Water Cerenkov response is based on the SuperK MC. LAr is modeled as a near-perfect detector.

Exposure is 3 MW. yr ν with $\sin^2 2\theta_{13} = 0.04$, $\delta_{cp} > 0$, $m_3 > m_1$

300 kT WCe **50 kT LAr**



Measurements of δ_{cp} in LBNE

Mark Dierckxsens

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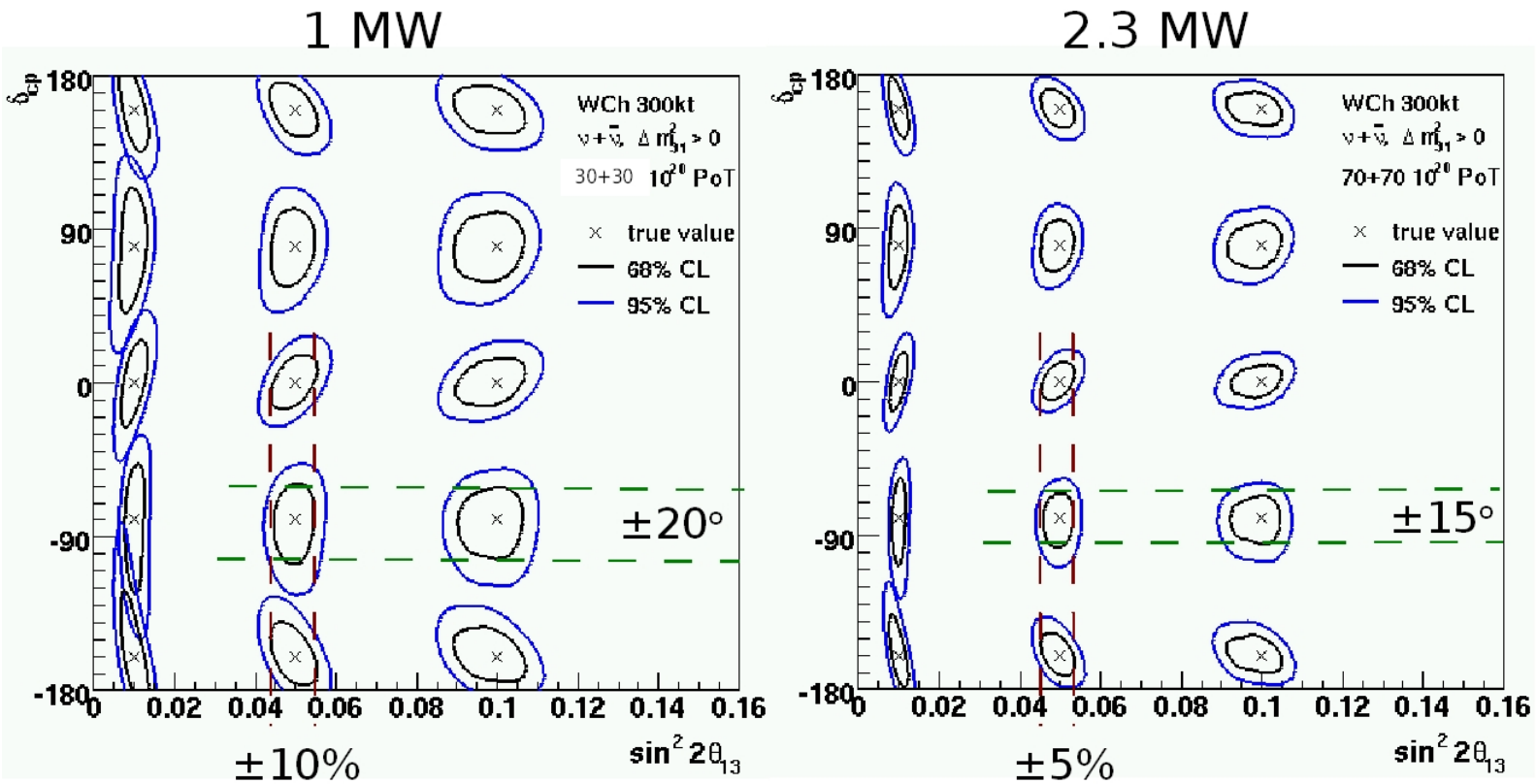
with a 300 kT WCe detector and 3 yrs of ν + 3 yrs of $\bar{\nu}$ running:

$(\theta_{13},\delta_{cp})$ Measurement



Precision measurement of δ_{cp} for $\sin^2 2\theta_{13} \geq 0.01$

Summary and Conclusions

3 flavor neutrino mixing is now well established.

BUT- what we dont know is even more important:

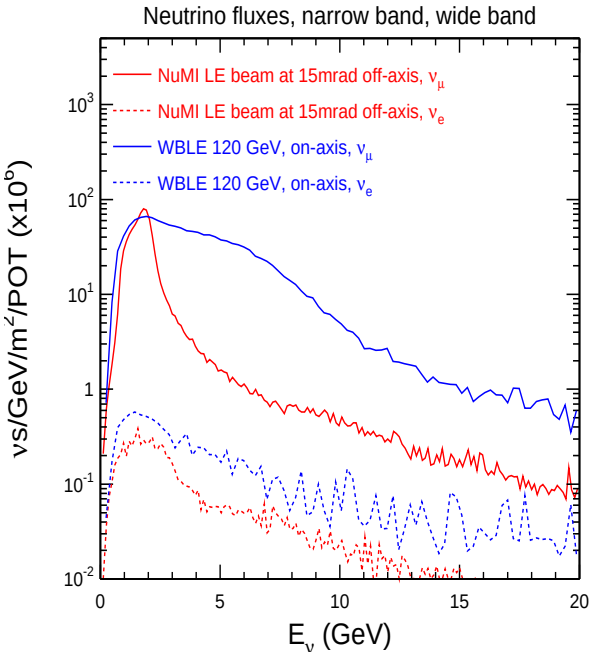
- **What is the mass of ν_μ?**
- **How small is $\sin^2 2\theta_{13}$? Is it close to the current limit (0.1) or is it very small? Is it 0?**
- **Is there CP violation in the lepton sector?**
- **What is the mass hierarchy?**
- **Are there only 3 generations of leptons?**

In the coming decade, reactor and accelerator ν experiments ($\mathcal{O}(100-1000)$ M\$), will be able to determine if $\sin^2 2\theta_{13} > 0.005$ and can measure δ_{cp} and the mass hierarchy for $\sin^2 2\theta_{13} \geq 1\%$.

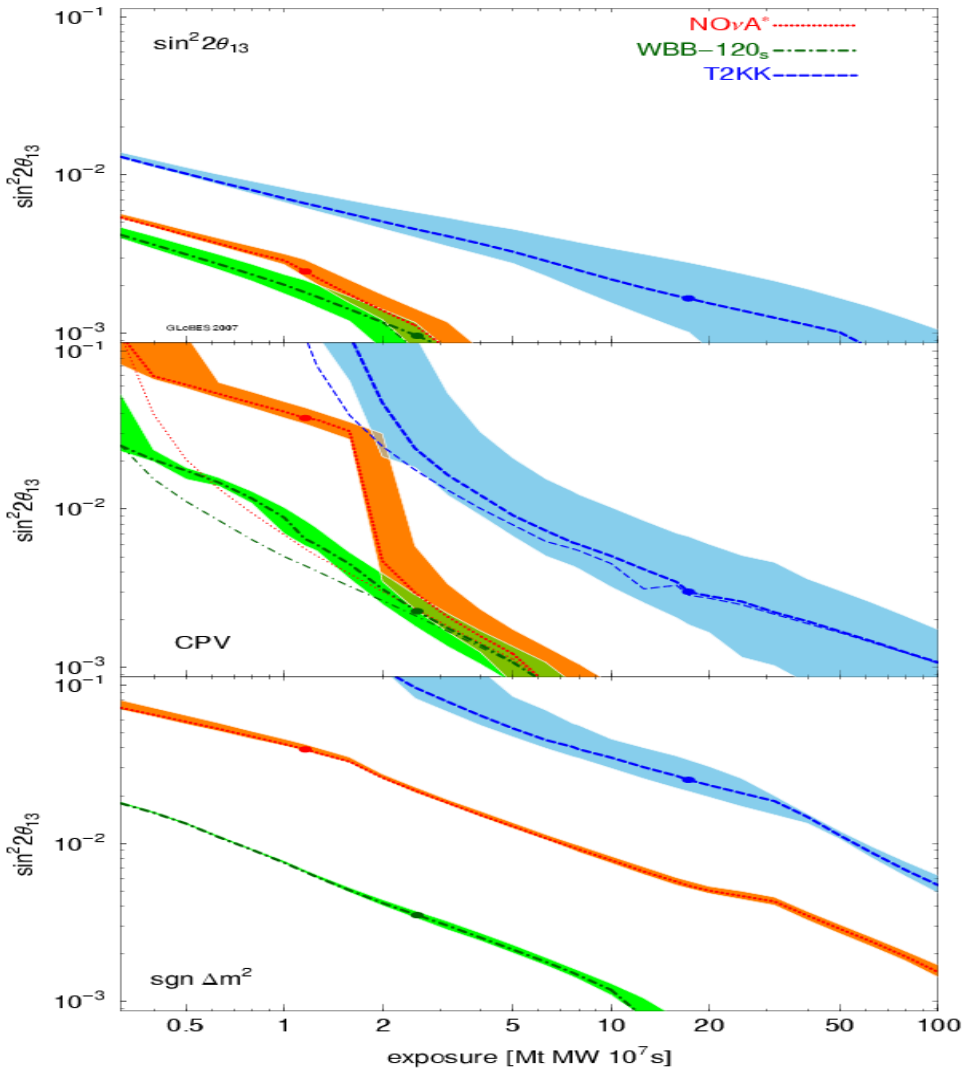
EXTRA SLIDES FOR DISCUSSION

Sensitivity vs Exposure

The potential physics reach from studies with the 120 GeV WBLE-DUSEL at 1300km using a LAr detector, the NOνA experiment and the T2KK experiment:*



From hep-ph/0703029:



Non Standard Interaction Sensitivities

300 kt WCe, 1MW beam, 3 yrs ν + 3 yrs $\bar{\nu}$

Joachim Kopp, FNAL

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Neutrino oscillations including NSI

$$P_{\nu^s_\alpha \to \nu^d_\beta} = |\langle \nu^d_\beta | e^{-i(H+V_{\rm NSI})L} | \nu^s_\alpha \rangle|^2 = |\langle \nu^d_\beta | (1+\varepsilon^d) e^{-i(H+V_{\rm NSI})L} (1+\varepsilon^s) | \nu^s_\alpha \rangle|^2$$

- CC type NSI: Flavour mixture at source and detector (Grossman PL **B359** (1995) 141)

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta} |\nu_\beta\rangle, \qquad \text{e.g. } \pi^+ \xrightarrow{\varepsilon^s_{\mu e}} \mu^+ \nu_e$$

$$\langle \nu^d_\beta| = \langle \nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^d_{\alpha\beta} \langle \nu_\alpha| \qquad \text{e.g. } \nu_\tau N \xrightarrow{\varepsilon^d_{\tau e}} e^- X$$

- NC type NSI: Extra matter effects in propagation

Wolfenstein PR **D17** (1978) 2369, Valle PL **B199** (1987) 432, Guzzo Masiero Petcov PL **B260** (1991) 154, Roulet PR **D44** (1991) R935, etc.

$$(V_{\rm NSI})_{\alpha\beta} = \sqrt{2} G_F N_e \varepsilon^m_{\alpha\beta}$$

Non Standard Interaction Sensitivities

300 kt WCe, 1MW beam, 3 yrs ν + 3 yrs $\bar{\nu}$

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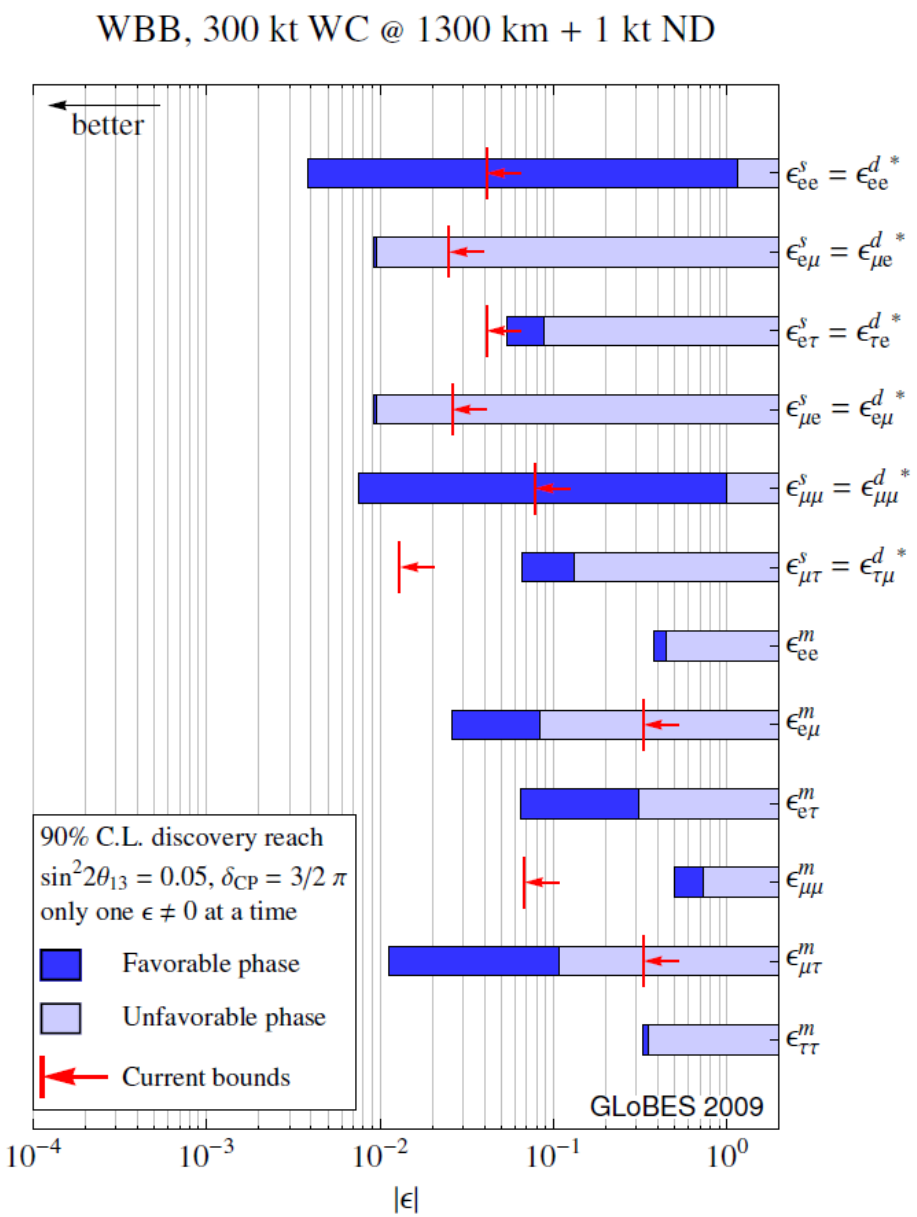

Bounds can be improved up to one order of magnitude.

Current bounds from arXiv: 0907.0097